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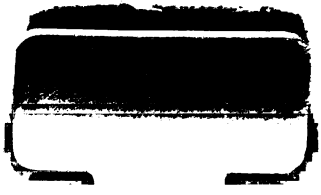

TURBINES

TURBINES

BY

W. H. STUART GARNETT

OF THE INNER TEMPLE, BARRISTER-AT-LAW

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PREFACE.

IT was my intention, when I first undertook the task of writing this book, to give a popular account of the history, construction, and operation of the turbine, and particularly of the various steam turbines which are attracting, and very properly attracting, so much public interest. In the course of its growth the work has been somewhat modified by my experience of the extraordinary ignorance prevailing among men of some degree of technical knowledge, and even among competent engineers, of the very nature of this, one of the simplest and most beautiful among modern machines, the heir of all the ages of engineering experience and development.

It is undoubtedly very much to the credit of the technical institutions of this country, that the engineers who leave their doors after a three years' course should be masters of that most complicated mechanism the reciprocating steam engine, but I cannot but think it a pity that these students

181021

should spend long hours in drawing valve diagrams and studying the advantages of steam jacketting, to the exclusion of any notice of a simpler prime mover which bids fair in course of time completely to displace the reciprocating engine from the market. I have endeavoured, therefore, while bearing in mind the paramount necessity of producing a book intelligible and, I trust, interesting, to the amateur, to call attention to those points and problems which deserve the more particular notice of the student.

With this object, I have, in the fourth and sixth chapters of Part I, awarded to questions of blade design, and to other details of like importance in the construction of steam turbines and of water turbines, a rather more intimate consideration than some readers may consider necessary. The pages are in the reader's hand to turn when he will.

For the rest, it has been my object to trace the development of the science of turbines, as it appears to have grown in the minds of the inventors responsible for its material manifestations; and I am confident that the reader who has studied the problems solved and the difficulties overcome by the pioneers of the water turbine, will approach the subject of the more modern and more interesting steam turbine with a full appreciation of the scientific principles underlying its action.

I desire to express my thanks to the Hon. C. A. Parsons, C.B., F.R.S., for his very kind and valuable assistance in the section dealing with the excellent engine that bears his name, and to other engineers whose machines are described in these pages. The courtesy of the Librarian of the Royal Society and of his staff has enabled me to offer a brief review of the history of the water turbine, and my thanks are due to him and to many others who have taken an active interest in the work.

W. H. S. G.

3, Temple Gardens,
Temple, E.C.
April, 1906.

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PART I

WATER TURBINES

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CHAPTER I.

SOME EARLY ENGINES.

THE primary object of science in general, and of mechanical science in particular, is the application of the forces of nature to the service of man. The more intelligent and the more idle of mankind have alike sought means of lightening the daily task by the service of some animate or inanimate agent. So in 1713 a boy left in charge of a pumping engine lightened his duties by the invention of the self-acting steam valve, and made possible the modern steam engine; and so no doubt men have been continually seeking a key to the stores of energy which Nature has provided.

Energy exists in a great variety of forms, chemical as in coal, electrical as in a thunder-cloud, mechanical as in a lake raised above sea-level, or in a flowing river; and in the last form its presence is fairly obvious to the casual observer. It would not require any great intellectual effort in a savage, who daily saw trees carried along on the surface of a river, to conceive the idea of utilizing the same agent for the transport of his own roof-tree when he wished to build him a house; and so it is probable that, far back in the prehistoric ages, the rivers of Asia performed, in the service of man, the work that the Ottawa and the Oregon do to-day. But it was not for transport only that power was required in early days:

the ancient Egyptians and the savages who preceded them ground their corn in a hand-mill, as many peoples do at present, and for relief in this, and in many other directions, a stationary supply of natural power was eminently desirable. The obvious source of power was the river, and the problem was to derive from its rectilinear motion a form of motion mechanically useful, which yet should not remove the machine in which it existed away from the spot at which power was required: a motion, that is to say, of rotation. The solution of this problem was the water-wheel, described by Vitruvius in a book written in the fourth century B.C. This is probably the oldest of the power-giving engines invented by man; and indeed the first machine of his ancestors appeals so strongly to the modern boy that there are probably few children to whom a stream is available who have not at some time made a rudimentary model for themselves. Not that the early water-wheel was itself anything but rudimentary, consisting as it did of a heavy wheel with wooden paddles or floats, set in the circumference and standing out radially all round: the inner end of the axle turning in a bearing built into the wall of the mill or house where the power was required, and the other end carried on a post or pier standing in the stream.

Such a machine did very well in early days, but, as population and competition increased, more work was required of the mill, and the miller began to notice its defects, especially the very obvious one that a great part of the water flowed past without touching the wheel at all. To remedy this, a dam, or weir, was put across the river, and the greater part of the water was led down a mill-race and through a narrow channel where it could not well pass the wheel without acting on its floats. Now it is evident that at every point in the race or channel the

same amount of water must go past in one minute (for all that comes in at one end travels along and leaves at the other), and it follows that where the channel is narrowest the water must flow fastest, so that at the mill itself the speed must be very great; and for this to be the case there must be a considerable difference in the water level before and behind the mill; in other words the level of water in the head race must be considerably above that in the tail race, and the water, therefore, passes the

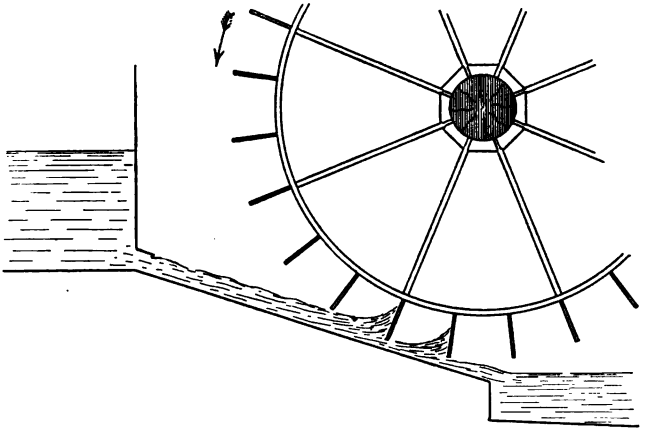

FIG. 1. UNDERSHOT WATER-WHEEL.

mill on a slope. As the modifications were carried further the machine reached the form (shown in the figure) in which it was used by the Romans, and in which it is used still in a great many parts of England.

It must not, however, be supposed that these were the only lines along which development took place in early days. Long before the undershot water-wheel had reached the stage which we have just described, a number of other sources of natural power had been tapped. Wind was used both for transport and for power supply. Early

windmills consisted, indeed, simply of a number, usually four, of masts, with flat sails set obliquely on them, stepped, like spokes, in a hub, so as to balance one another and to revolve, instead of moving to and fro as they would do in a vessel reaching. Such mills were used in this country, and in Holland, soon after the days of William the Conqueror, and were the only ones known until Biram, in the year 1842, suggested the idea of curving the sails, and introduced the many-bladed windmill which has since, particularly in America, developed enormously. It is worth noting that the action of a windmill depends on the pressure of the moving fluid on a plane inclined to its direction of motion, that is, on the principle of the screw; so that when the time came for the screw propeller and the other uses of screws of which we shall have occasion to speak, an example was at hand in the windmill to illustrate this method of conversion of rectilinear into rotary motion.

Another early engine, the overshot water-wheel, has for its object the utilization of potential energy stored in high-level lakes and in water at the top of a fall. In this machine the weight of the water is used, the vanes of the wheel being set against the drum and between two annular plates or shrouds. These vanes are so curved as to form, with the shrouds and drum, buckets capable of holding water. The water runs down a short sloping culvert or spout, from which it shoots across the top of the wheel, and after striking the vanes with a slight impulse, partially fills the buckets and carries them down, till, near the bottom of the wheel, it is poured out into the tail race. The overshot wheel has this advantage over the other, that the water is poured out from the moving buckets in a direction opposite to that of their motion, and is consequently left almost at rest. Unlike the water

which drives an undershot wheel, it gives almost the whole of its motion to the machine. The overshot wheel is a highly efficient engine when applied to falls having a small flow of water, and not less than twelve, nor more than forty, feet in height. For higher falls it has been proposed, notably by Fussel in 1803, to arrange buckets

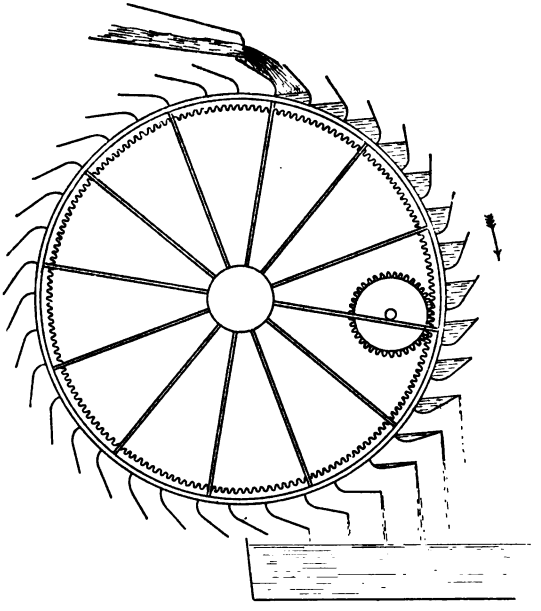

FIG. 2. OVERSHOT WATER-WHEEL.

on a chain (as in a dredger) passing round wheels at the top and bottom of the fall, or to arrange a number of overshot wheels in series one above another, so that water falling from the bottom of one wheel enters the bucket at the top of the next. None of these arrangements, however, have been found commercially satisfactory, and they have all now given place to the high-speed water turbine.

One more application of natural power deserves mention in this place, though the tracing of its further development must be postponed to a later stage of our work. Hero of Alexandria, in his "Pneumatica," written in the second century B.C., described the first recorded utilization of steam to produce motion. The machine of which he wrote consisted of a sphere in which steam was generated over a lamp. The sphere was mounted in bearings, and free to rotate. From it the steam escaped by means of two narrow tubes set opposite to one another in a diameter of the sphere; each of these tubes was bent over at the end and narrowed into a fine jet, through which the steam was expelled in a direction at right angles to the axis of rotation; these two jets faced in opposite directions, and the action between the steam and the pipe, which forced the steam out of the jet, forced the jet itself backwards, so that the sphere rotated with considerable velocity. This machine was not, however, applied to any practical use until the year 1784, when it was revived, or perhaps re-discovered, by De Kempelen, who took out a patent for it in that year. Another use of a jet of steam was made in the year 1629 by Giovanni Branca, who drove a small mill-wheel by the impact on its vanes of steam issuing direct from a boiler.

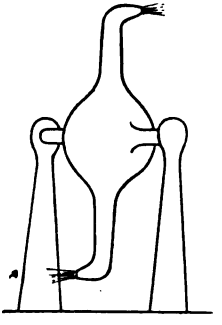

FIG. 3. THE EOLOPYLE (*circa* 150 B.C.).

Between the days of this machine and that of De Kempelen self-acting steam valves were introduced, and great progress was made with the reciprocating steam engine, so that attention was to a certain extent diverted from the simple rotary engine, and in fact, for forty years

after De Kempelen's time, very little progress was made with rotary machines for either steam or water power; but it is worth noting that these two machines, invented by Hero in the second century B.C., and Branca in the seventeenth century A.D., exemplify, though very imperfectly, the two principles of action and re-action on which is based the whole theory and practice of turbine engineering.

CHAPTER II.

THE EVOLUTION OF THE WATER TURBINE.

IT will be evident from a consideration of the principles enunciated in Appendix I, that the old undershot water-wheel was open to serious criticism on the ground of inefficiency, and, as more and more was required of machinery, it became necessary to bring about some improvement in the design of these wheels. The gravest defect of the undershot wheel was, that, while, owing to the narrowing of the channel necessary to bring all the water passing to bear on the wheel, the speed of the water in that part of the channel was considerable, yet the speed of the wheel itself was small. If rapidly moving water had to strike a slowly moving float, there was a great loss of energy by impact; if, on the other hand, the wheel were arranged to work at a high speed, then the water, being discharged at the speed of the wheel itself, carried off with it the greater part of the energy which should have been supplied to the machine.

To obviate these disadvantages it was required to design a wheel in which there should be little if any impact between the water and the floats, but in which, nevertheless, the water should be left by the wheel almost without motion. It was pointed out that water, on leaving the curved buckets of the overshot water-wheel, remained almost at rest, so that it may not unreasonably be sup-

posed that floats similar in shape to the buckets of the overshot wheel would be an improvement on the flat boards formerly in use on the undershot wheel; and in fact General Poncelet, in the year 1826, suggested improvements in the undershot wheel, consisting of a channel so narrowed and shaped as to fit the wheel very closely for some distance, and of floats of a shape rather like

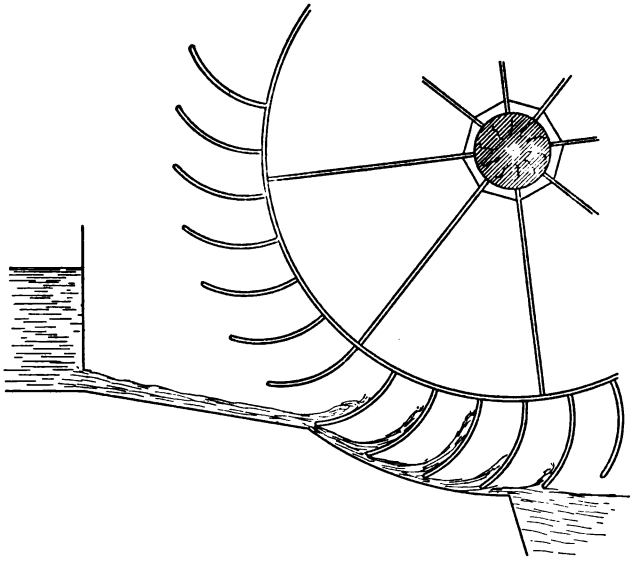

FIG. 4. PONCELET WHEEL (1826).

that of the overshot buckets. The wheel was situated as before at the lower end of a sloping channel, and the form of the machine was that shown in the accompanying figure.

The curved floats of the Poncelet wheel had another advantage besides that already set forth, namely, that the water approached the floats tangentially, and wasted no power in impact; it ran smoothly up the blades press-

ing on the curved surface, and ran back still so pressing, leaving the wheel at last entirely without motion. Thus the Poncelet wheel was a highly efficient engine, differing only from the true turbine in that the fluid approached and left the blades by the same edge, and this machine is still in common use where a low speed is wanted and the available head of water is small.

It was Carnot who first enunciated, in 1787, the two propositions illustrated by the Poncelet wheel, that efficiency could only be obtained by a water engine if the fluid entered it without impact and left it without energy. Poncelet, in a paper published in 1826, claims very properly that his wheel satisfies the requirements of Carnot.

In a paper published by M. Burdin two years later, the same virtues are claimed for an engine of quite a different type. This is the first wheel described by the name turbine, and belongs to a different class from the early turbines already described. To understand its origin and development we must go back for a moment to see what was being done in this country a hundred years before.

The precise significance, in engineering practice, of the term "turbine," an adaptation of the Latin *turbo* (which means a top) made by M. Burdin for the purpose of distinguishing his invention, has never, apparently, been defined. The practice of eighty years, for Burdin's first machine was constructed in 1824, has, however, so far fixed the meaning of the term that it is now fairly easy to predicate of any particular machine whether or no it will fall into the class of turbines, and the following generic description of this engine will perhaps serve to discriminate between the machines which deserve to be classed as turbines and those which do not:—

"A turbine is a rotary engine in which power is derived from the pressure of a fluid on the sides of channels

in the rotating part, which channels the fluid traverses in one direction only, approaching the rotor with velocity in the direction of rotation, and leaving it wholly or partly deprived of that velocity."

If this definition of a turbine be accepted, then the first recorded turbine is probably that described in M. Belidor's "Architecture Hydraulique" as being in common usage on the Garonne at the date of the book, 1737. The ac-

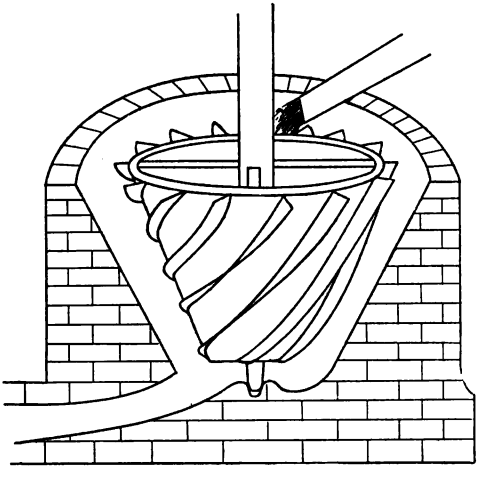

FIG. 5. GARONNE TURBINE (*circa* 1730).

companying figure (Fig. 5) is taken from that work, and fairly indicates the nature of the machine. Sloping blades run round a cone from base to vertex, the cone being mounted on a shaft and set in a conical pit, which should fit the outer edges of the blades as closely as possible; water is introduced to the machine by a sloping channel in such a manner as to strike the blades at right angles; and after sinking to the bottom of the pit (acting on the blades all the time), it finally escapes by a channel.

The action of the machine can be easily followed.

Suppose the water to enter the pit with velocity, V, due to a fall, H, then for efficiency the angular velocity of the cone should be V/R, where R is the radius of the cone at the top. The water then enters the pit without impact, and forms part of a vortex in which every particle of water has the same angular velocity about the axis, namely, the angular velocity of the conical wheel. Now as the water, under the action of its weight, sinks lower in the pit and approaches more nearly the axis of the wheel, so its velocity and angular momentum are continually diminished; and when it reaches the bottom it has actually very little motion, and is finally, if the machine is well designed, completely deprived of angular momentum and almost of its velocity.

This machine is, therefore, if properly made, a turbine of no mean merit; the early forms were, however, as may be seen from the figure, of a very crude type, for the constructors were largely ignorant of the advantages of their own machines. Indeed, so distinguished an engineer as Belidor himself dismisses them with the curt notice that many curious wheels of the form shown may be seen in operation on the Garonne, and that their speed is considerable; he then goes on to speak of the installation of le Basacle as worthy of deep consideration.

In this mill, wheels of the form of ventilating fans were set in the bottom of the head race channel, and through them the water escaped into the tail race. M. Belidor very prudently declines to enter into a mathematical discussion of these wheels, but states that, for the best results, the fans or blades should be set at an angle of thirty-five degrees with the horizon. We shall so far follow M. Belidor as to pass over the theory of these wheels, simply remarking that they are not true turbines, as the water enters them without velocity in

the direction of motion; but they belong to the large class of reaction wheels—wheels, that is to say, which depend for their motive force on the reaction of fluid, which enters without velocity in the direction of rotation, but leaves with large angular momentum in the opposite sense. At a very high speed they have a fair efficiency.

Of such reaction wheels perhaps the most typical, and, with the exception of Hero's engine, described in Chap. I of this book, probably the first, was Barker's mill, invented by Dr. Robert Barker about the year 1730. This machine was an application to water of Hero's engine, and consisted of a long horizontal barrel, called the trunk, mounted on a vertical axis, and pierced by two orifices at opposite ends of the trunk, opening in opposite directions. Into this trunk water was led from the head through a sleeve joint in the hollow axis which supported it; and this water, escaping through the orifices at the ends of the trunk, caused it by its reaction to rotate in the manner of a tourbillon. A shaft ascending from the middle point of the trunk was mortised into the upper mill-stone.

It will be evident that this machine satisfies the first of the requirements enunciated by Poncelet, for the water enters it without impact and is gradually accelerated, each particle moving from the centre along a path somewhat similar to that sketched out in figure 7, till at A it attains the velocity of the end of the trunk. During this time the pressure of the water is, thanks to centrifugal action, being continually increased, and when it comes to A at the end of the trunk, the pressure on one side of the stream being suddenly removed, it receives a very rapid acceleration in a direction opposed to that of its previous motion, and is ejected from the orifice into the air just above the tail race of the mill.

This machine is, of course, very far from satisfying the

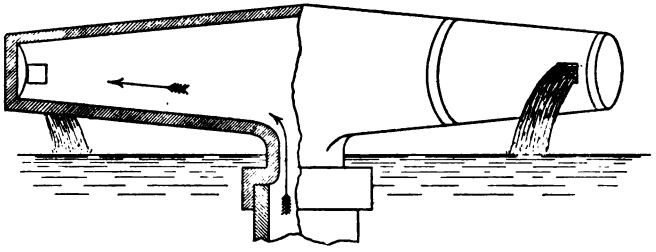

FIG. 6. BARKER'S MILL (1730).

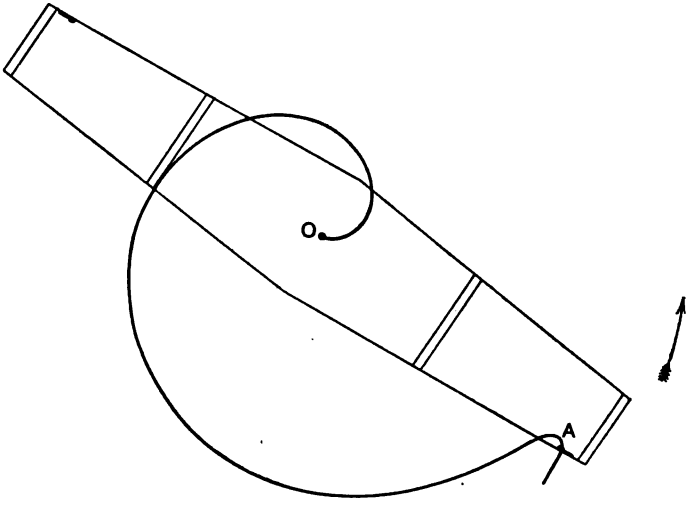

FIG. 7. PATH OF WATER IN BARKER'S MILL.

second of Poncelet's requirements, for it is of the very essence of its action that the water should leave it with considerable velocity. The efficiency will only be high if the speed of the rotor is high in comparison with that of the escaping water; this implies a low head and a high speed of rotation. Since, however, the head, H, is to be small, a large output requires a large flow of water, and therefore the section of the trunk must be large. The mass of the trunk, together with that of the water in it, is therefore very great, and, as this mass is to be driven at a high speed, much power will necessarily be wasted on pivotal friction. A limit is thus set to the speed at which it is wise to drive the machine, and in practice a peripheral speed of $\sqrt{2GH}$ is found to give the best result.

The theoretical efficiency of Barker's mill under the best conditions of working is 0·828, and owing to the mechanical difficulties of which we have spoken, this efficiency has never been even approached in practice; in fact, in spite of comparatively recent improvements in construction, and in the shape of the arms, in consequence of which their section and weight can be much diminished, Barker's mill, as a source of power, is now obsolete. It has, however, furnished some ingenious toys, an example of which is the neat little lawn sprinkler, with which most of our readers are probably familiar.

Now, if the reader will examine the path (sketched in Fig. 7) followed by the fluid in the trunk of the simple mill, he will observe that the whole forward thrust on the mill is exerted at A, where the stream bends sharply, and that in flowing outwards it continually receives angular motion from the machine, and consequently exerts on it a backward pressure. If, instead, this angular motion were communicated to the water before it entered

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the rotor, a great increase in efficiency would result; and this is precisely the improvement effected by M. Burdin in his machine of 1824. He also secured that the water should leave without velocity.

The rotating part of this machine consisted of a tank, from which the water was discharged, as from Barker's mill, in a direction opposed to that of rotation. The water entered the tank just within the circumference,

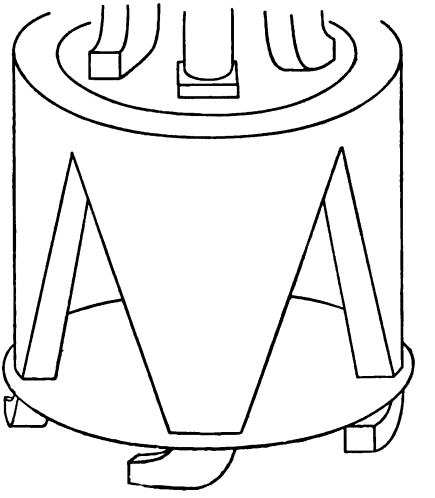

FIG. 8. BURDIN'S TURBINE (1824).

from horizontal nozzles, with considerable velocity in the direction of rotation. The nozzles were set in the bottom of the head race.

If the head of water above the nozzles be H, then the velocity with which the water enters the tank must be $\sqrt{2GH}$, and in order that all impact should be avoided at the entrance, the velocity of the tank at the circumference should be the same, so that, if the radius of the tank be R, its angular velocity should, for high efficiency,

be $\sqrt{2GH}/R$. To satisfy the second condition of efficiency the water must leave the tank without velocity, and therefore its velocity of discharge through the nozzle should be equal, as it is in any case opposite, to the velocity of the nozzle itself. In order to acquire this velocity, $\sqrt{2GH}$, relative to the orifice, the water must be discharged under a head H, so that the depth of water in the tank should, for satisfactory working, be H.

The theoretical efficiency of this machine is perfect, so that, if there were no mechanical losses, the output would be the whole work done by the fall. The mechanical losses are, however, great. The depth of the rotating tank must be one half of the height of the fall, and its weight is therefore very great in comparison with the power developed. The only method of regulation is by a sluice gate, and whether the power or the speed of the machine is altered, a great loss of efficiency is the result.

In spite of its disadvantages, Burdin's turbine is worthy of study as representing the first conscious effort to produce an engine the importance of which the public are, even now, only beginning to realize.

Scientific men had, however, appreciated the possibilities of such an engine to some extent, even before the appearance of this turbine. In 1823, the Société d'Encouragement de Paris had offered a prize of 6,000 francs to the inventor of a water-wheel similar to those described by Belidor, which should be of real commercial utility. For eleven years no inventor worthy of the honour made his appearance, and then, in 1834, the prize was awarded to M. Fourneyron, who produced a machine incomparably superior to any then existing. The design of this turbine has scarcely required modification to meet the exacting requirements of the present day.

CHAPTER III.

THREE PIONEERS.

THE obvious defects of the Burdin turbine arose from the fact that it was necessary to have, in the rotor itself, a considerable difference of level between the point where the water entered without either pressure or velocity, and the point at which it was to acquire a velocity of discharge, relative to the machine, equal to that of the machine itself, and at which a considerable pressure was therefore necessary.

This velocity of discharge the fluid must have for efficient working, whether it be steam, water, or gas; and this velocity it can acquire (if it has not had a velocity relative to the rotor during the whole of its passage through it) in two ways only, namely, by the action of gravity, or else by the pressure of the fluid behind. For the first action to take place, the rotor must be large enough to give gravity an opportunity of doing the necessary amount of work on the fluid during its passage. Generally the rotor will have to be, as in Burdin's machine, half as high as the fall. For the second action, namely, acceleration by fluid pressure, the rotor need not be large, but, since the pressure drops continually as the speed increases, the water must enter the wheel at considerable pressure.

On the other hand the water may have at all times

during its passage through the wheel the necessary velocity relative to the wheel, and in that case neither of these actions is necessary.

The problem, then, which the Société d'Encouragement set in 1823 to the engineers of the day, resolved itself into that of doing away with the necessity for the great height of Burdin's rotor, and this, as we have just seen, involves the admission of fluid to the wheel, either at a considerable pressure or else with a velocity relative to the wheel equal to that of the wheel itself at the point of admission (App. II). It may be thought that so great a velocity or pressure at admission is not necessary if the fluid is to leave the wheel at a point near to the axis, where the velocity is small; but this impression would be erroneous, for considerable pressure or velocity will be required to overcome the centrifugal action of the rotating water within the wheel, and in fact it will be found, when we come to enter more fully into the theory of water turbines, that the necessity for admission at high velocity or else under pressure remains entirely unaffected by the relative positions of the points of admission and discharge (App. II).

Fourneyron, 1827.

Having regard to the fact that Poncelet published in 1826 a description of the undershot water-wheel which goes by his name, we ought perhaps to give him some credit for the form of the first satisfactory solution of this problem. The turbine which Fourneyron constructed in 1827, and described in a paper presented to the Society in 1834, has, in the form of its blades at least, a distinct resemblance to the Poncelet wheel. This machine is shown in elevation and plan in Figs. 9 and 10.

The external diameter of the wheel was 6 feet, and

the internal diameter 4 feet $2\frac{1}{2}$ inches. The blades were circular, and perpendicular to the rim at their inner ends, resembling very much those of the Poncelet wheel. At the outer ends they made an angle of 15° with the circumference. The whole wheel was formed of a single casting.

As may be seen in Fig. 9, the wheel surrounds the bottom of a fixed pipe or well, from which water enters the moving channels. The direction of the water at entrance into the wheel is determined by guide blades of the spiral form shown in Fig. 10. These guides are inclined at an angle of 45° to the rim of the wheel, so that they bisect the angle between the rim and the moving blades.

Fourneyron found that the machine worked almost equally well above and below the tail water, but the best result was obtained when it was set above the surface and under a head of 4 feet. The turbine then gave a torque of 561 pound-feet at 50 revolutions per minute. This amounts to a rate of working of 2,940 foot-pounds per second or 5·35 H.P. The flow of water was then 845 pounds per second, and the work done by the fall was therefore 3,380 foot-pounds per second. This shows an efficiency in the machine of 87%, an efficiency still unsurpassed.

Poncelet investigated the theory of this wheel in 1838, and maintained that the highest efficiency should result from a speed of the inner rim equal to $\sqrt{0{\cdot}6}$ of the free velocity due to the fall. If he is right, the speed of the wheel in the circumstances above set forth should be $56\frac{1}{2}$ revolutions per minute.

An investigation of the theory of this simple turbine will conduce to an understanding of the more complicated engines, and may be very briefly conducted.

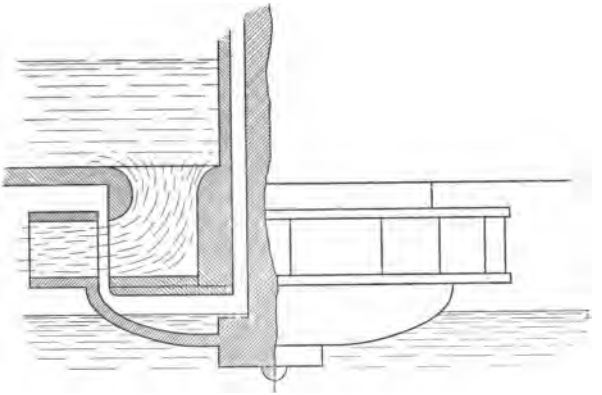

FIG. 9.

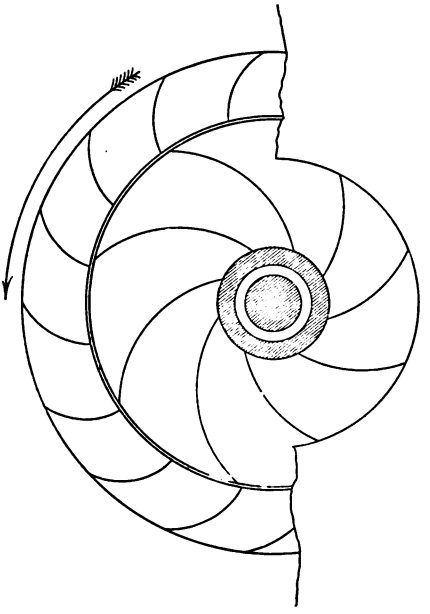

FIG. 10. FOURNEYRON'S TURBINE (1827).

The velocity of the water as it emerges from the guiding channels is that due to the head of 4 feet, a velocity of 16 feet per second. This is made up (App. I) of a velocity of 11·3 feet per second along the rim and 11·3 feet per second along the radius; that is to say, along the moving blade. Now, if there is to be no impact, the blade must have the same velocity of 11·3 along the rim. According to our theory, then, the speed of the inner rim should be $\sqrt{\frac{1}{2}}$ the free velocity due to the fall, and the speed of the wheel will then be $51\frac{1}{2}$ revolutions per minute, very nearly the speed found experimentally by Fourneyron.

Now the velocity of the water along the blade at the inner end is 11·3 feet per second, the velocity of the wheel at the same point, so that if the water were discharged from the wheel at the inner rim in a direction opposite to that of the wheel's motion, it would be at rest after discharge. As the water flows outwards, centrifugal force increases its speed, but the speed of the wheel increases at the same time; and it is shown in App. II (Vortex Motion) that these increases are equal. It is clear, then, that if the water were discharged from the outer rim of the wheel in a direction opposite to that of the wheel's motion, the velocity of the water after discharge would be nil. This state of things is very nearly realized, and the turbine therefore satisfies the two requirements of Carnot, when running at the correct speed.

The necessity of clearing the discharged water away from the wheel makes it impossible to satisfy completely these requirements, and the water is discharged, as stated above, at an angle of 15° with the rim. The path of the water in this turbine is very like that in Barker's mill, with the difference that the fixed channels—an essential feature of a turbine—shape the earlier part of the curve.

Fourneyron soon went on to the construction of larger

machines, which were, for the most part, built up of wrought iron, and not cast like the early one. The third of these was built in 1833, and was designed to give 20 H.P. under a fall of 1·3 metres or about 4 feet 4 inches. The machine actually developed 50 H.P. and was the most powerful hydraulic engine of its day. It was found that it could be run with only slight variation of efficiency under any heads between 7 inches and 8 feet.

In all these larger turbines Fourneyron adopted the precise design of the original wheel, with the modification that the crown of blades was narrowed, in proportion to the diameter of the wheel, for the purpose of keeping the weight within reasonable limits. Though the angles of the blades and guides were not varied, none of these later engines met with the same success as did that resulting from the first attempt.

For working at low loads it was necessary to regulate the machines, and this was done in the later ones by a very economical method; the height of the orifices in the fixed drum, by which the water escaped into the wheel, was altered by a sluice worked from above by a worm-wheel. This sluice was so curved that it did not narrow the channel suddenly, but allowed a smooth flow of water.

The gravest defect of the turbine, and that which to a certain extent unfitted it, and unfits others made on the same principle to-day, for many engineering purposes, was the exceeding want of stability of its motion when running under a heavy load. Under these circumstances the speed of the wheel would be somewhat, and might be considerably, below the theoretically best. When this was the case not only was the efficiency lowered, but the fact that water entered the wheel with impact caused

a back pressure outside the orifices of the fixed drum, and thus reduced the speed of the water entering the wheel, and consequently the total flow of water. Now if the load on the turbine were reduced for an instant, the speed of the wheel would increase, causing a corresponding increase in the centrifugal action and diminution in the impact, which would both tend to diminish the back pressure and so to increase the flow, and which might even increase it out of proportion to the increase of speed, so that the torque exerted by the wheel would actually increase and the acceleration of the wheel would continue for some time. The result of this peculiarity of the turbine would be a ludicrous exaggeration of the phenomenon known in the case of steam engines as hunting; and, for electric and other work in which steady speed is required, this vice to a great extent puts the Fourneyron turbine out of court.

It has been remarked that the efficiency of Fourneyron's experimental machine, under the best conditions, was 87%, a result which was equalled by some elaborate machines constructed on similar lines in 1837 to give 190 horse-power, but which does not appear to have been surpassed by any outward flow turbine. This is in part due to the fact that in the larger wheels the crown was narrower and the blades more numerous, so that some strangulation of the flow took place in the wheel, causing a certain amount of pressure at the point of admission and completely upsetting the theory on which the wheel was originally designed.

This trouble was remedied by Girard in a modified form of the Fourneyron turbine, of which we shall speak hereafter. The Girard turbine is free from the vice of instability and has almost entirely displaced the original form from modern practice.

JONVAL, 1837.

Another of the varieties of turbine in modern use owes its origin to Jonval of Mühlhausen, who, in 1837, designed and constructed a machine in which the blades and guides were set round cylindrical drums, so that the water in its passage through the wheel remained always at the same distance from the axis. Such turbines are known in this country as axial or parallel flow machines, and on the continent as Jonval turbines.

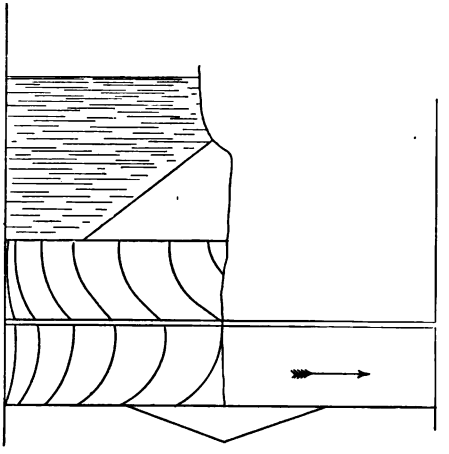

FIG. 11. JONVAL TURBINE (1837).

The machine consists essentially of two wheels, of which one is a reversed copy, or reflection, of the other. The inner part of each wheel is solid and bounded by a cylindrical rim. Between it and a concentric exterior rim of the same width are fixed blades, dividing the space between the rims into channels. These blades, shown in the accompanying figure are vertical at the top, and are bent so as to make an angle of about thirty degrees with the horizontal at the bottom, differing in the

two wheels only in this respect, that they are bent in opposite directions. The upper wheel is fixed, so that water entering it vertically from the pit, of which it forms the bottom, is deflected on to the blades of the moving wheel. This is situate immediately below the other, coaxial with it, and fitting with as little clearance as possible.

The whole flow through each of the wheels of the Jonval turbine is the same, and the section of the channel at any point in the moving wheel is the same as the section at the corresponding point in the fixed wheel; so that, if the channels are always full, which it is clear that they must be, the velocity of the water relative to the wheel at any point in the lower wheel is equal to the velocity of the water at the corresponding point in the upper wheel. The velocity of the water relative to the wheel at the point of discharge is, therefore, equal to its absolute velocity at the point of admission; but, in order that admission should take place without impact, the horizontal velocity at admission must be equal to the velocity of the wheel, and the horizontal velocity relative to the wheel at discharge must accordingly also be equal, and in this case opposite, to the velocity of the wheel. The water, therefore, leaves the wheel without horizontal motion, but with considerable vertical velocity.

We will reserve for another place the discussion of the theoretically best velocity for the wheel, but we may say here that the most satisfactory results have been obtained, with speeds of the outer circumference equal to from 3/5 to 2/3 of the free velocity due to the fall.

In modern practice there is a great variety in the forms of the blades used in axial flow turbines, as in those of every other type, but, in the machines which most nearly resemble the early one of Jonval, the principal change is

a slight increase in the curvature of the guides, by reason of which their discharge ends are more nearly horizontal than those of the moving blades; the consequence of this is that the water leaves the wheel with a diminished vertical velocity but with a slight velocity in the direction of motion.

Jonval's turbines were usually set above the level of the tail race, and they discharged into a suction pipe. By this means an excellent clearance of the discharged water was secured, while the benefit of the whole available head was obtained.

The output of Jonval's turbine in its original form was regulated by a sluice in the supply pipe, which diminished the flow of water through the machine. Since, however, the sluice had the further effect of diminishing the effective head, this system caused a serious loss of power on light loads, and has long been abandoned in favour of more efficient methods.

The solution offered by Jonval to the problem set out at the beginning of this chapter differs from that of Fourneyron primarily in this, that the water is not entirely dependent for its velocity of discharge on the velocity with which it enters the wheel, but rather on the pressure with which it enters, and which accelerates it gradually as the passage through the wheel narrows. The solution of the problem which we have still to consider presents this difference from that of Fourneyron in a still more marked degree.

Howd, 1838.

A third class of turbines are driven in the manner claimed in the specification of the United States Patent granted to S. B. Howd in 1838. This specification describes a turbine designed for low falls, and whose con-

struction is of the simplest. The wheel, cast in one piece, resembles that of the Fourneyron turbine in general construction, but the blades, being designed for inward flow, are concave to the circumference, and their curvature is comparatively small, the angles which they make with the inner and outer rims of the crown being about 30° and 75° respectively. The upper face of this wheel is a solid disk, and the lower a ring, so that the water, leaving the blades at the end near the axis, can escape downwards, through the hole in the lower face, and so into the tail race. This wheel fits closely inside a case formed by two annular plates in the same planes with the faces of the wheel. Between these plates are straight guides meeting the wheel at an angle of 20°. From the outside of the case a cylinder rises to the surface of the water. The output of the machine is regulated by a sluice gate sliding on the outside of this cylinder, and operated by a lever to cover wholly or partially the channels between the fixed guides. The accompanying illustration is taken from Howd's patent specification (Fig. 13).

Unfortunately, no figures are now obtainable as to the performance of this machine; its efficiency was certainly much lower than that of Fourneyron's turbine, but it had the advantage of extreme simplicity, cheapness, and compactness, which, in a country like America (where, at that time at least, water power was much more plentiful than capital) was of more importance than economy, and secured for it great popularity. All the preparation required for this machine was the construction of a conduit to lead the water off from a hole in the bottom of the head race; the turbine set down on top of the hole could be run, regulated, and stopped without further trouble.

In view of the advantages which it possessed, it is not surprising that in 1849, when J. B. Francis, of Lowell,

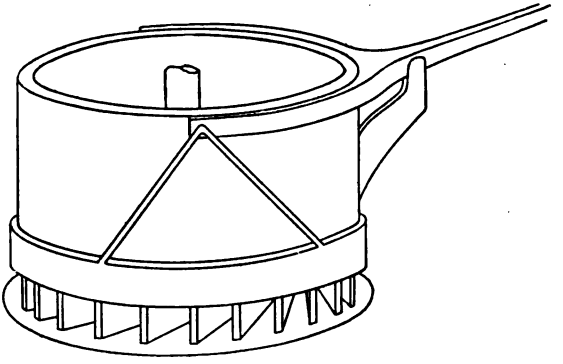

FIG. 12.

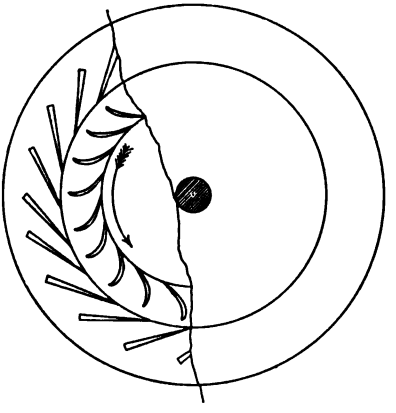

FIG. 13. HOWD'S TURBINE (1838).

Mass., took this turbine in hand with a view to its more scientific construction and improvement, there were already a very large number of the machines in operation in the United States.

Francis conducted experiments on a very considerable scale in connection with turbines, sluices, and other hydraulic machinery, of which investigations an excellent account will be found in his book, "Lowell Hydraulic Experiments." One of the wheels, the subject of these studies, was designed by him in 1849, and is really an improved form of Howd's machine, the straight guides having given place to curves, and the angle of the blades being considerably altered. The diameter of this wheel, which was capable of giving 230 H.P. under a fall of 19 feet, was 11·338 feet, and the height of the wheel at the exterior circumference was 1 foot, while at the inner end of the blades it was 1·23 foot, or 23 per cent. greater; a feature of the design which suggests that Francis himself did not fully realize that, to obtain a satisfactory result, the speed of the water relative to the wheel should increase during its passage through the wheel, and that the water should enter under pressure. Instead of permitting this to take place the designer would appear to have been at some pains to secure that the channel should not narrow to any great extent, so that the water entered only under slight pressure, and was not greatly accelerated in its passage. Now as the direction of the stream at entry does not nearly bisect the angle between the blade and the direction of its motion, as it does in the case of Fourneyron's turbine, this involves the condition that the water must either enter with impact or else leave with velocity, according to the speed at which the wheel is run.

Francis found that the best result was obtained from

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the wheel when the speed under a fall of 13·378 feet was 0·6719 revolution per second, the speed of the circumference being then 0·672 of the free velocity due to the fall. It is pretty evident that under these circumstances there is considerable impact at admission, a fact which Francis himself observed and was somewhat at a loss to explain, seeing as he did that it involved some defect in the design of the turbine. Francis was also surprised to find that under these most favourable conditions the efficiency of the wheel was only 0·797, but in view of our observations as to the design, we are more inclined to wonder that so good a result was obtained.

Turbines made on this plan have from the time of Howd been the most popular in America, though for a long time European practice favoured the Jonval type; and it appears that at present, for low falls at least, turbines with external admission are ousting, even from the Continent, machines of every other design.

CHAPTER IV.

A THEORETICAL DISCUSSION OF TURBINES.

WE have already seen that a turbine will act in a satisfactory way only if the fluid enters the wheel either under pressure or else with a velocity relative to the wheel, and this is true alike of water and of steam turbines, and it must be true of every other form of turbine which the future may bring forth. The exact relation between the pressure and velocity with which the fluid enters the wheel must be the first subject of our investigation.

The conditions to be satisfied are twofold, and were laid down in the year 1787. They are that the fluid must enter the wheel without impact and must leave it without velocity.

The first condition is comparatively unimportant where steam is concerned, on account of its elasticity, for there can be no true shock on an elastic body (App. I). The second condition, however, applies equally to every working fluid.

With hydraulic engines, the first condition is of supreme importance. It implies that, if the water enter the wheel with velocity relative thereto, that velocity must be along the blades; if it were not so, there would be impact on the blades.

The pressure of the water at the point of discharge is the pressure outside the wheel; it may be atmospheric,

but in many modern machines it is below the atmospheric pressure. For our present purpose we shall speak of it as zero pressure. It will then be understood that a pressure of ten pounds means a pressure of ten pounds above that at the point of discharge.

Now the second condition implies that the velocity of the fluid, relative to the wheel, at the point of discharge, shall be equal to the velocity of the wheel at that point (and in the opposite direction). The outer surface of the wheel moves more quickly than the inner surface, but, if water is discharged from the outer surface, its motion is accelerated by centrifugal force as it flows through the wheel; if it flows inwards, the motion is correspondingly retarded, so that it is immaterial (as is more fully explained in App. II), to our consideration of the second condition from what part of the surface discharge actually takes place. We shall assume, then, that the fluid is discharged, as in a Jonval turbine, at the same distance from the axis as that at which it enters the wheel.

If, then, the velocity of the wheel at the points of admission and of discharge be V, the velocity of the fluid relative to the wheel at the point of discharge must also be V. Now, if the fluid enter the wheel without pressure, as is the case in the turbine of Fourneyron, and in very many steam turbines, the velocity of the fluid relative to the wheel at the point of admission must be V, the velocity of the wheel at the point of admission.

Suppose, however, that the fluid enters the wheel under pressure. It is shown in App. II that a stream of water may move with a velocity varying from point to point, according to the section of the channel in which it flows, and that the pressure of the water varies also, the law connecting pressure and velocity being

$$P + \tfrac{1}{2}MV^2 = \text{A Constant}$$

(P being the pressure per square foot in absolute units, and M the mass of a cubic foot of water). The same law holds good for small expansions of steam.

Now, if we consider the stream of water in one of the wheel channels, the constant of this stream must be equal to the value of $\frac{1}{2}MV^2$ at the point where P is nothing, that is, at the point of discharge. If then the water were to enter the wheel without velocity relative to the wheel (a state of things impossible to realize), the pressure per square foot at the point of admission should be $\frac{1}{2}MV^2$, V being the velocity of the wheel at the point of discharge, and also at the point of admission.

Considering what takes place in the two turbines discussed, we can see that the difference between the pressure-velocity changes taking place between the guide blades in the two cases is really this, that, in the first, all the pressure of the water is converted into motion between the fixed guides, before it enters the wheel; while, in the second case, of the same total pressure enough only is converted to give the water the velocity of the wheel and none relative thereto. The commonest case, however, is intermediate between these two; and, what is there necessary is that the constant of the motion at admission should be the same as in the two previous cases; that is to say, if the water enter with a velocity U along blades moving with velocity V, the pressure of the water should be $\frac{1}{2}MV^2-\frac{1}{2}MU^2$; the pressure necessary if the water were to enter without velocity, less the pressure necessary to produce the velocity which the water actually has.

According to the system of admission, turbines are divided into two classes. Those of the first class, in which the water enters the wheel without pressure, are known in England as impulse turbines, and on the

Continent, for the most part, as turbines of free deviation. An example of this class of machine is Fourneyron's turbine running at the theoretically best, or any higher velocity. The second class of machines consists of those in which the water enters the wheel under pressure, either with or without velocity relative to the wheel; these machines are known in England as reaction turbines, and are well exemplified by Thomson's case wheel, and by Fourneyron's turbine, when running at less than the normal speed. It may serve to fix the distinction between these two classes of machines, to suggest that they consist, as to the first class, of developments of Poncelet's water-wheel, and, as to the second, of developments of Barker's mill, though neither of the two patriarchal engines is itself a turbine proper.

There is another system of classification of these machines; classification, namely, according to the arrangement of the blades. Provided the fluid enters the wheel with velocity in the direction of rotation and leaves it wholly or partially deprived of that velocity, there is no restriction on the path which it may follow within the machine, and in fact a great many different arrangements of the blading are used. For the most part however the blades are set either in the plane of rotation, forming a radial flow turbine, which is an outward or inward flow (Francis) machine according to the path of of the water, (of these, Fourneyron's and Howd's turbines are the earliest examples); or else on a cylindrical surface, forming the parallel flow turbine, of which Jonval's is the archetype, and in which the acting fluid maintains an invariable distance from the axis.

Besides these, there are machines of the type generally described as "conical flow," exemplified by the early turbines of the Garonne, described in a former chapter,

and by the less strictly conical variety of the same machine, patented, together with his case-wheel, by James Thomson in 1850. There is also a great variety of turbines, not very clearly distinguishable from the "conical flow" group, in which the water enters by the internal or external surface and leaves by the bottom, or enters by the top and leaves by the circumference, or follows some other devious path. A large number of these are made nowadays, and are classed together as "mixed flow" turbines, among which the "conical flow" machines are often grouped. These varieties are, however, only matters of form, and, although no doubt some forms give rather better results than others, there is no difference of principle involved, and this classification is consequently of much less importance than the one which we have previously mentioned, and to which we shall now return.

Firstly, then, let us consider the machines of the "impulse" type. In these the water is at atmospheric pressure during the whole of its course through the wheel, and therefore will not, generally, press on both sides of the channel through which it flows. For this reason it is not necessary that the channel should always be full, or that it should be designed to fit the stream which passes through it; all that is necessary is that there should always be room in the channel for the water to pass, while pressing only on the blade by which the machine is driven.

In the parallel flow impulse turbine, the speed of the water relatively to the wheel is the same at admission and at discharge, and throughout the motion, so that the section of the stream does not alter at all in the course of its passage through the wheel. In designing a parallel flow impulse turbine, it is, therefore, necessary to secure that the section of the channels is not reduced, at any

point, below the section of the stream at the point of admission; an increase in section on the other hand does not affect the machine in any way. In radial flow impulse turbines, the speed of the fluid will, owing to the influence of centrifugal action, alter between admission and discharge, increasing in the case of outward flow, diminishing in the case of inward flow; and so, while the section of the channels may in an outward flow turbine be, as in the Fourneyron wheel, contracted towards the point of discharge—a result naturally following from the form of the blades—the section in an inward flow turbine, must be expanded towards the centre, and this to such an extent as to render the design of an inward flow impulse turbine almost impossible; and, in fact, we are not aware that any such have ever been constructed.

The modification of the section of the channels can be achieved after the form of the blades has been fixed (though not quite so efficiently as by properly forming the blades) by the arrangement of the upper and lower surfaces of the channels, and is therefore a secondary consideration. The first problem—given the type of machine to be constructed, the available fall and flow, and the speed and power required of the machine—is to settle the forms and inclinations of the guide curves and blades, which are to determine the path of the water, and to communicate its driving power to the turbine wheel.

Suppose, then, that AB represents the velocity of the wheel at the point at which the water is admitted, and AC the direction of the blade at this point. The water must at admission, as we know (p. 35), possess the velocity represented by AB, together with an equal velocity along the blade, that is, in the direction AC, so that if we complete the parallelogram ABDC, the line AD will represent, in magnitude and direction, the whole velocity

which the water ought to possess at admission, in order to give the best result (App. I). This direction bisects the angle BAC; and it is the direction of the guide blades that determines the direction of the stream; we may, therefore, take it as one of the first principles of design of an impulse turbine that the inclination of the guide curve to the rim should be one half of that of the blade. It may be slightly less without loss of efficiency.

The direction of the guiding curves, therefore, depends on that of the blades at the point of admission, or, as we shall call it, the beginning of the blades; and this, as will appear hereafter, depends to a large extent on

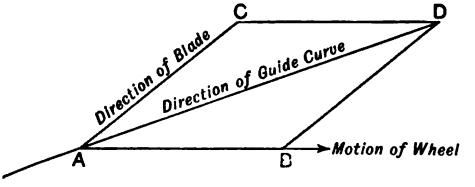

FIG. 14.

local considerations. Of the proper directions for the ends of the blades, however, there can be no doubt; it is required of them so to direct the efflux of water that it leaves the wheel as far as possible without motion, and their directions should, therefore, be as nearly opposed to that of the wheel's motion as is compatible with a proper clearance of the discharged fluid. For an outward flow turbine Fourneyron found an angle of 15° sufficient; this is large enough for a parallel flow machine, but in an inward flow wheel it should be rather larger. The same considerations control the discharge of reaction turbines, so that these remarks may be applied to them with equal force.

The beginning angle of the blade has now to be determined, and this depends principally on the speed at

which the machine is to run. In Fig. 14, AD represents the velocity of the water at admission, *i.e.*, the velocity due to the fall, and AB represents, on the same scale, the velocity of the wheel at the point of admission; and it is quite clear that the relation between AB and AD depends on the size of the angle BAC; if, for instance, BAC were very small, AB would be little more than half AD. It is, in fact, clear enough that, if the beginning of the blade is almost—it may even be quite—parallel to the direction of the wheel's motion, then the water must have double the velocity of the wheel; and as the angle BAC increases, so also does the ratio of AB to AD. When the angle is a right angle we have the case of Fourneyron's turbine, and the velocity of the wheel is $\sqrt{\frac{1}{2}}$ (or 0·707) of the velocity due to the fall. If the angle between the convex side of the blade and the wheel be increased above 90°, the velocity of the wheel is still further increased; thus, when this angle is 120°, and the blade, the guide, and the circumference of the wheel are all equally inclined to each other, the velocity of the wheel is equal to the velocity due to the fall; and if the angle were large, that is to say, if the concave surface of the blade were to make a small angle with the reversed direction of motion, the velocity of the wheel for high efficiency would be much greater than the free velocity due to the fall.

For the purpose of driving dynamos, for which turbines are now largely used, a high speed (500 to 1,500 revolutions) is required, and if the available fall be small it may be very desirable to produce a relatively high blade speed; but an impulse turbine is a very unsuitable one for the purpose, and for this reason:—In order that the discharged water may clear the wheel, the ends of the blades must be inclined at 15° or so to the direction of motion,

and, if the beginnings of the blades be inclined at only a small angle, the blades will be nearly straight. Now an impulse turbine derives its motion from the change in the direction of flow of the fluid as it passes along the blades, and, if the blades are nearly straight, then the change cannot be a prolonged and steady one, but must take place, to a great extent, when the water first meets the blades; the turbine is then driven by impact, which is fatal to efficiency.

Impulse turbines, then, are unsuited for the development of high speed motion from low falls, a function which must be left to machines of the other type. For running, on the other hand, at low speeds under a high fall, the impulse turbine cannot be surpassed.

The forms of impulse turbine in most general use are the outward flow Girard turbine and the parallel flow Pelton wheel. The latter is commonly used for the very highest falls. Descriptions and illustrations of both these machines, as made by some leading firms, will be found in the next chapter.

The directions of the blades at their beginnings and ends being determined, we have to settle the curve they are to follow between the two limits, as well as their number. These are matters in which experience is a far better guide than mathematical reasoning. Bearing in mind, then, that the water must exert a steady pressure on every part of the blade, and, to do this, must flow in a smooth curve, the designer of hydraulic machinery, like the designer of ships, must to a great extent rely on experience, and on the look and feel of the curves. We shall, therefore, confine ourselves at this place to a few general remarks, referring the reader for further detail to the drawings of modern machinery set out in the later chapters.

In dealing with this part of our problem, it will be well to consider not only the path of the fluid relative to the wheel, but also its actual path in space, and we may begin by sketching either the one or the other; when one is drawn the other is also determined. Suppose, for instance, that we draw out the path to be followed by the fluid in space. We know that the total velocity at any point is made up of the velocity which the water has in common with the wheel, and an equal velocity along the blade; and it follows that the direction of motion in space at any point bisects the angle between the direction of motion of the wheel and the direction of the blade at that point. We can, therefore, from the direction of flow in space, construct the direction of the blade at any point, and to plot the blade is then a very simple piece of geometry. It will, however, be found advisable to draw, first, the proposed shape of blade, and to test this by plotting the curve in space followed by the fluid during its passage through the wheel.

If we bear in mind the fact that the fluid meets the blade not only at the beginning, but also at all points within some small distance of the beginning, depending on the breadth of the jet, we can see that, to avoid impact, the blade should be almost straight for a small distance at the beginning; and, in order that the water may be discharged without eddies, the blade should be straight, or nearly so, for a small distance at the end. In designing a blade for a Pelton wheel whose velocity is to be half of the free velocity due to the fall, we should adopt a form something like that shown in the accompanying figure (Fig. 15).

Having now determined the form of blade to be adopted, we proceed to find the path described by the fluid in the following way. The velocity of the water along the blade

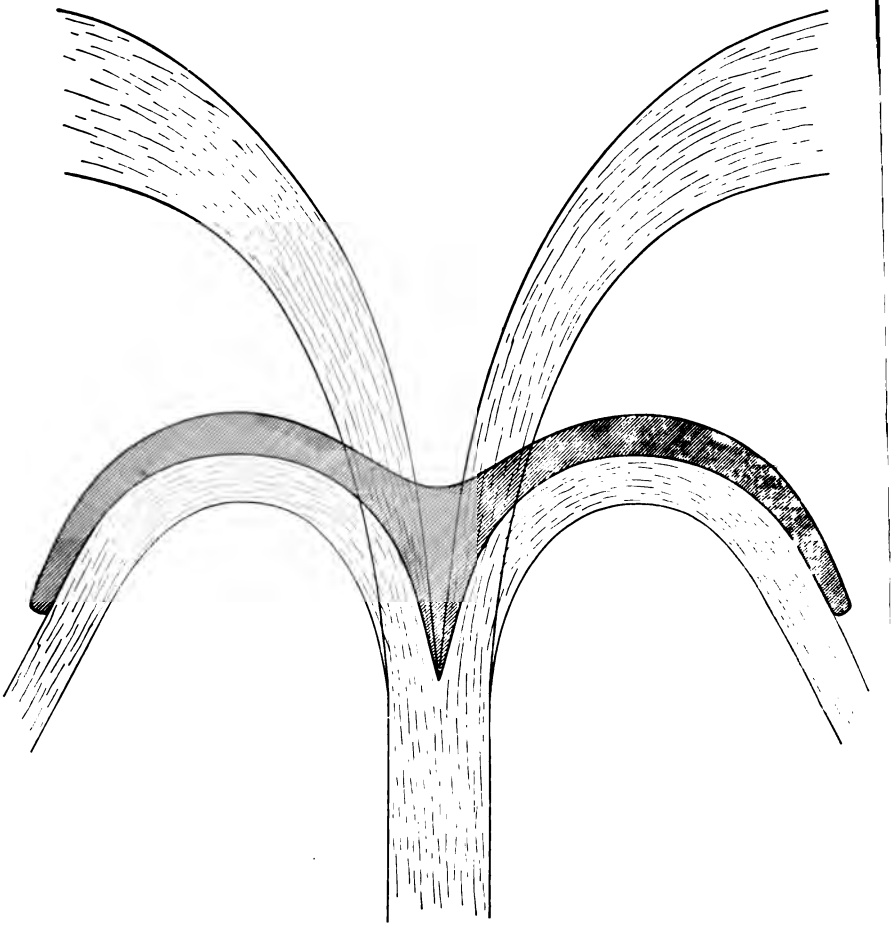

FIG. 15. TRUE AND APPARENT FLOW OF WATER IN PELTON BUCKET.

is uniform, and so is the velocity of the blade itself; accordingly, if we choose any particular point on the blade in its present position, then the fluid which meets the blade at the knife will have reached this point on the blade when the point has moved from its present position through a distance equal to that travelled by the fluid along the blade. So we find a point on the path through space of the particle of water which met the blade at the knife. If then we take a number of points —preferably at equal distances along the blade—we can in this way construct the position of a number of points on the path of the particle of water, and so draw the curve which it follows, precisely as we have drawn the curve in the accompanying figure. This, then, is the curve described by one side of the stream past the blade—that side, namely, which touches the blade itself; to draw the curve described by the other side of the stream we must first draw the curve on the wheel which is the margin of the stream through the wheel. Now the velocity of flow relative to the wheel being uniform, the width of the stream in the wheel is uniform, and its bounding curve may be sketched in. Having this curve we construct the other from it exactly as before.

A study of these curves of flow of the liquid in a turbine will explain in a very clear and graphic manner the nature of the action which takes place. For instance, the curvature of the stream in space shows that some force is acting on it to change its direction, and that consequently it must be pressing on the blade of the wheel. The increasing width of the stream shows that its velocity in space (though not relative to the wheel) is continually diminishing, and that it is therefore doing work on the wheel.

But we have not yet finished with the problems of

design before us. We have to consider the proper number of the blades and the number of fixed guides or nozzles to be used in the machine. We have already remarked that impulse turbines are used chiefly in connection with high falls, and when only a moderate speed is required; and, the fall being high, only a small flow of water will be necessary to give considerable power. Now it is not possible to design a turbine in which the blades shall move with less than half the free velocity due to the fall, and in which the efficiency shall still be high; and the free velocity may be very large indeed. In the case of a 200 feet fall, for instance—and such a head is not unusual—the velocity is 120 feet per second, so that the blades must move with a speed of not less than 60 feet per second. If at the same time it is necessary, as for the direct driving of certain machinery, that the speed of the shaft should be moderate, it will be necessary to use a wheel of great diameter.

If the whole circumference of a wheel of such diameter were to be surrounded with nozzles, the flow of water would be immense—unless the nozzles were mere sprays, unsuitable for engineering purposes—and this in a case where only a small flow is required. But in a turbine of free deviation it is not necessary that the channels of the wheel should always be full, or should even have any water at all in them throughout the motion, and it will therefore be sufficient to place only one or two nozzles at the circumference of the wheel, which shall bring each blade into action once or twice in the course of its revolution. This is, in fact, the practice adopted in connection with the Pelton wheel and with the Girard turbine, in each of which only one or two nozzles are used.

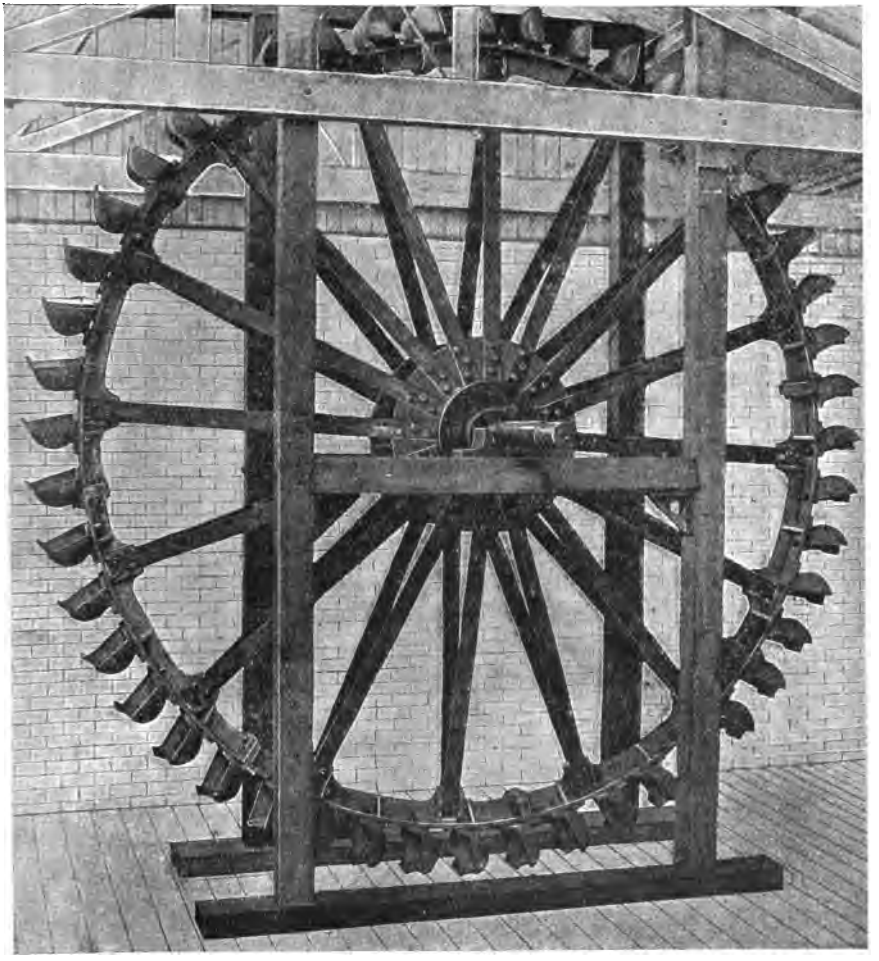

FIG. 16. LOW SPEED PELTON WHEEL UNDER CONSTRUCTION.
(GILBERT GILKES AND CO., KENDAL.)

CHAPTER V.

MODERN IMPULSE TURBINES.

AN examination of the statistics published by any of the large firms will show that by far the larger part of their output at the present day consists of the wheels which we have classed as reaction turbines. While, however, the number of reaction turbines in use increases by leaps and bounds, the number of impulse turbines is also advancing steadily; for the two diff' ent types are no longer in competition, and it is now very generally recognized that, while the reaction machine can most advantageously replace the old water-wheel, the impulse wheel is the proper machine for very high falls, where the flow of water is often insufficient to fill the channels of a reaction turbine of such size as to give the required slowness of motion.

There are only two impulse turbines in common use at the present day—the Girard turbine and the tangential wheel, well known in this country in the form of the Pelton wheel—and of these we will now speak.

Tangential Wheels

We have discussed the Poncelet wheel of 1825, the first wheel in which shock at admission was avoided by causing the water to enter in a direction tangential to the floats, and we have pointed out the objection to classing this

wheel among turbines, that the water approaches and leaves the blades by the same end. This anomaly makes it necessary that the height of the floats should be at least a quarter of that of the fall; otherwise, when the wheel runs at the proper speed, the water will rise to the tops of the floats, and waste its energy in impact on the drum.

The Poncelet wheel therefore laboured under the disadvantage of being suitable only for very low falls; a disadvantage which was not overcome till 1856, when Cheetham produced a wheel in which the blades were modified in form, so that the water, instead of rushing straight up to the drum of the wheel, was diverted to the sides, and there thrown off in a direction nearly opposed to that of its entrance, so as to be practically deprived of motion.

In this wheel of Cheetham's, then, the blades were become very like buckets, and, as the water was received in the middle of these, and the stream there divided, it may be said that each of these buckets consisted really of two turbine blades joined at the admission ends, so that the tangential wheel was in fact a double turbine. This general construction of a tangential wheel has been adhered to ever since its first appearance, but the manner of setting the wheel is now very much altered. It is usually mounted on a horizontal shaft, directly connected to the dynamo or other machine to be driven; the required speed is obtained by giving a suitable diameter to the wheel. Below this the stream is concentrated in a single horizontal jet discharged from a nozzle, the line of the jet being, as the name of the machine suggests, tangential to the circle of the wheel.

As the turbine turns, bucket after bucket drops into the stream, moves along in it, subject all the time to impulse

of the water, until it is gradually eclipsed by the next bucket, which pares away the jet. In a few cases, where it is desired to obtain considerable power from a small

FIG. 17. HIGH SPEED IMPULSE WHEELS.
(ESCHER WYSS AND CO., ZURICH.)

wheel, as when a high speed of rotation is required, two jets are used, but better results are generally obtained by keying two single jet wheels on the same shaft.

An enormous variety of impulse wheels is turned out

by the different manufacturing firms, ranging from the 21 foot wheel, illustrated in Fig. 16, running at 36 R.P.M., and developing 200 H.P. under a fall of 96 feet, to the 9 ft. 10 in. wheel, recently constructed by the Pelton Water Wheel Co. of San Francisco for a fall of 865 feet, which develops 5,000 H.P. at a speed of 225 revolutions (Fig. 19). Some of the many forms of wheel manufactured are illustrated in Fig. 17; it will be noticed that they differ chiefly in the shapes of the buckets, which are formed of two spherical or cylindrical cups. These are the results

FIG. 18. PELTON WHEEL RUNNING.
(PELTON WATER WHEEL CO., U.S.A.)

of many costly experiments, as well as of a good deal of somewhat unprofitable theorizing, to which we, for our part, would be loth to add, but it may be interesting to take some slight notice of the points to be considered.

A bucket is required which will enter the jet without unduly breaking it or deflecting it from the bucket beyond—will receive every particle of the water with the least possible shock—distribute it over the surface of the metal so as to reduce the wear, always very considerable,

to a minimum—and will finally discharge it as nearly as possible without motion.

In order that the latter function may be performed, and at the same time a satisfactory clearance obtained, it is desirable that the buckets should be set at some distance apart, and that the water should be discharged from a great part of the rim at once. The buckets must, however, be set closely together if the cylindrical form without a base is used, as in some of the wheels in Fig. 17, since, if the water continues to act on one of these buckets after it is past the perpendicular, some of it is bound to escape from the bottom, and that with considerable velocity. The spherical or ellipsoidal form of cup is open to the objection that the whole stream is concentrated at the vertex in every position of the bucket while in action, and this part is therefore liable to rapid erosion.

The cylindrical form with a sloping base, generally known as the Pelton bucket, which is very well shown in Fig. 19, would appear to be fairly free from objection, and the high efficiency of 82½ per cent. has been obtained with wheels of the Pelton type. It is claimed that, if losses behind the nozzles are neglected the true efficiency of the turbine is 86½ per cent. Messrs. Escher Wyss & Co. of Zurich have obtained 81·5 per cent. efficiency with baseless cylindrical buckets, in a 300 H.P. wheel, working at half load under a head of 508 feet.

In all these wheels, however well designed they may be, there is bound to be considerable erosion of the buckets, and when this is once started the stream lines of the water are affected, with the result that a perceptible decrease in efficiency is experienced; and the erosion, once started, generally proceeds with increasing speed. For this reason it is advisable, and, in the larger machines

FIG. 19. PELTON WHEEL.

at any rate, usual, to cast the buckets separately from the wheel, and to fix them with bolts so that they may be renewed after a few years' service.

Important as is the construction of the wheel itself, the design of the accessories and the conditions of running contribute equally to the efficiency of the machine. In the first place, the diameter of the stream at the point of entrance should never be more than 1/5 of the whole width of the bucket; if the stream is wide enough to make any approach to filling the bucket, it is not able to follow properly the curves of the blades, and eddies are set up; that part of the stream, too, which does not meet the knife, or central line of the bucket, wastes a great part of its energy in impact on the surfaces, round which it should glide smoothly. The losses due to excessive water supply are in fact so marked that nearly all the tangential water-wheels on the market will give a higher efficiency when running at half load than under the full load for which they are professedly designed—a fact to be borne in mind in setting up a power plant for a high fall.

Another source of loss in every turbine installation is the resistance to the flow in the pipe which conducts the water to the machine; and this may cause a serious diminution in the effective head behind the nozzle. Every such diminution of the effective head is to be avoided with the most anxious care; the rather that, of all the possible ways in which power may be wastefully expended, this is the one which gives least return of any kind.

This is a point of great importance in connection with the regulation of the machine. When the full power of the plant is not required, it is obviously necessary to reduce the flow of water, and this must be done in such

a way as not to diminish the effective head. To shut off the water above the turbine by a sluice gate, as is unfortunately a very common practice, is to use a system of regulation infinitely worse than that of controlling a steam engine by the throttle, a course which no modern engineer would willingly adopt.

FIG. 20. NOZZLE AND NEEDLE, SHOWING CLEANNESS OF JET. (PELTON WATER WHEEL CO.)

So far as it affects impulse turbines, the problem of control can be easily and satisfactorily solved by narrowing the nozzle, a proceeding which reduces the section of the stream without affecting its velocity (unless slightly to increase it if the resistance in the supply pipe is high). This is achieved in most tangential wheels by means of a needle forced into the nozzle, either by a screw turned by hand, or, as shown in Fig. 34, by some automatic

governing device. When it is required to reduce the power more rapidly than can be done by checking the flow, without danger of bursting the supply pipe, it is usual to deflect the nozzle so that the jet misses the buckets. The means adopted with impulse turbines of the Girard class is rather different, and will be described later.

We have now discussed pretty fully, omitting the more strictly technical matters of lubrication, scantling, and so on, the large and interesting class of turbines known as tangential wheels. Wheels of this type have been made for all powers up to 5,000 H.P., and for heads varying from 50 to 2,200 feet. We must turn our attention for a time to the other class of impulse turbines, known by the name of their inventor, Louis Dominique Girard.

Girard Turbines.

IN discussing the original turbine of Fourneyron, we made, and the inventor's experiments appeared to confirm, the assumption that the water entered the wheel moving freely under atmospheric pressure. In the later and larger machines, although manufactured on the same general plan, the narrowness of the crown in which the blades were set, and the increased number of the blades, made this assumption no longer tenable, as the constriction of the channels in the rotor caused considerable pressure at the point of admission. At the same time it would appear that these turbines were still designed as if they belonged to the impulse class, that is to say, with the guides bisecting the angle between the blades and the direction of motion, with the natural

consequence that none of these later wheels, in spite of the increased experience of the designer, showed so high an efficiency as the first which he constructed.

Nor is the diminished efficiency the only objection to running an outward flow, or Fourneyron, turbine as one of the "reaction" class, for, as we have already pointed out, the wheel is, under these circumstances, highly unstable in its motion and subject to the vice of hunting, a slight increase in the speed tending to diminish the pressure at admission, and so to increase the flow of water and the power, and to accelerate the wheel still further.

These defects may all be remedied by the cure applied by Girard in 1856, that of maintaining a constant section of the channels in the wheel by increasing the height of the crown towards the circumference; this secures what the inventor terms free deviation of the liquid within the wheel; and since it is not now requisite to maintain any pressure at the point of admission, it is no longer necessary that admission should take place all round the wheel; the number of fixed channels within the wheel is, therefore, greatly reduced, and in the modern machines it is usual to restrict the flow to one, or, at any rate, to a very small number of nozzles.

This partial admission makes it possible to run a wheel of considerable diameter with only a small flow of water, and a moderate speed of rotation is thereby secured, even when, as under a large head, the speed of the blades must be great. The Girard turbine is, therefore, well suited for developing the power of a high fall, when the flow of water is too large for a small tangential wheel, and the speed of rotation required makes a large tangential wheel unsuitable.

So it came about that this machine, which, at its in-

ception, found outward flow turbines almost displaced from the European market by those of the more recent

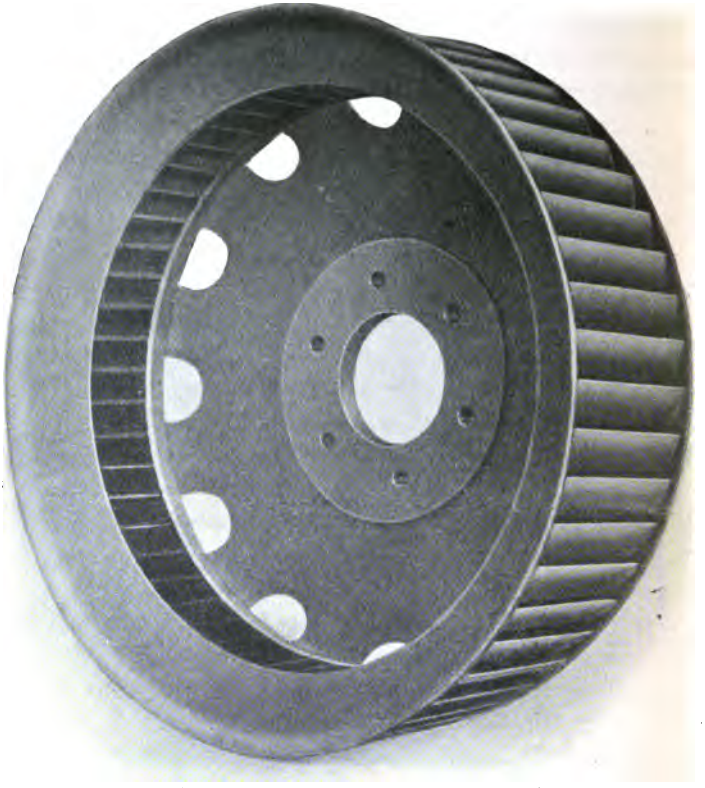

FIG. 21. "VICTOR" GIRARD RUNNER.
(STILLWELL-BIERCE AND SMITH-VAILE CO., DAYTON, OHIO.)

Jonval type, established, within a very few years, a recognized position as the proper wheel for use in connection with falls of 40 feet and upwards. It is true that of late years the Pelton wheel has largely displaced the

Girard for low powers, on account both of its extreme simplicity and of its suitability for the use of a very small stream of water; the high efficiency of the Girard turbine has, however, maintained its position for the development of large powers under heads too great for the Francis turbine.

In the detail of these, as of all other turbines, there is considerable difference between the European and American practices. According to the first system the rotor is usually built up of forged steel parts, while, according to the second, it is more often cast as a whole, the surface exposed to the action of the water being finished by grinding (Fig. 21).

The wheel here described (Figs. 22 and 23) is a turbine of 1,600 H.P., installed by Messrs. Piccard, Pictet et Cie., of Geneva, under a head of 590 metres (about 1,935 feet), at Gurtnellen, in Switzerland. The internal diameter of the rotor is 6 feet 6 inches, and its speed 500 revolutions per minute, so that the velocity of the blades at the point of admission is about 170 feet per second. At this speed, of course, there might be some danger of the crown, which is cast (Fig. 22), bursting, and so the makers have recourse to the following construction. The hub of the wheel is cast and keyed on to the shaft, and the crown is joined to this hub by a web of forged steel. Outside the crown, rings (B) of steel are shrunk on to the wheel, effectively strengthening the crown against the forces which might otherwise injure it. Should the crown, in the course of time, become worn away to any serious extent, it can be removed and replaced, without any change in the other parts of the wheel.

The essential feature of the Girard turbine is the form of this crown, which does not vary much. The shape

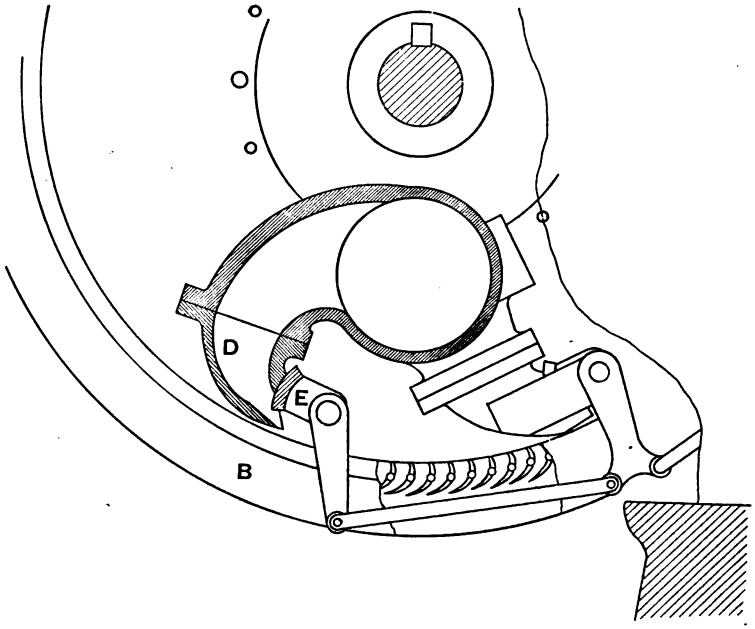

FIG. 22.

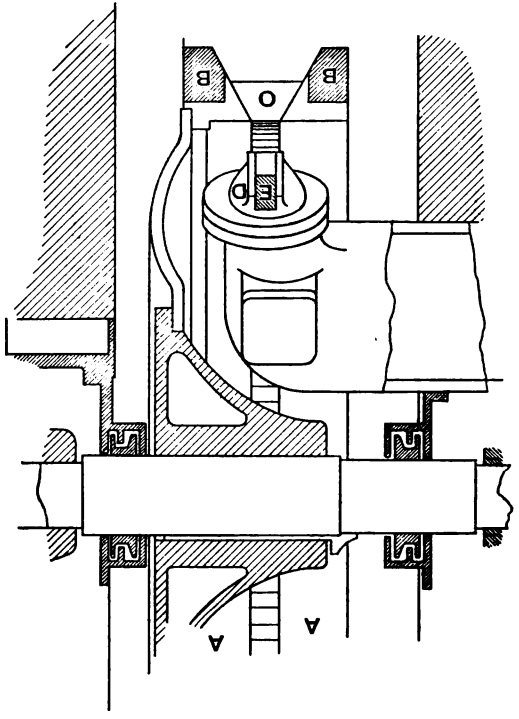

FIG. 23.

1600 H.P. GIRARD TURBINE AT GURTNELLEN.
(PICCARD, PICTET ET CIE., GENEVA.)

of the blades can be clearly seen in Fig. 22, which shows also the constriction in breadth of the wheel-passages inevitable in all outward flow turbines. Fig. 23 shows the increasing width of the blade (O), peculiar to the Girard turbine, which compensates this constriction by increasing the depth of the passages, thereby insuring free deviation of the water within the wheel.

As is proper in impulse turbines, regulation is effected by altering the width of the nozzles through which water is admitted to the wheel. These nozzles (DD), lined with phosphor bronze in order to resist the wear of the water, and the corrosive effect of the gases liberated when the pressure is relieved, are very well seen in Fig. 22. They are bolted directly to the two pipes forming the end of the pipe, and are furnished with cylindrical gates (E) by means of which the openings can be reduced from their full width of 6 centimetres to anything that may be desired. These gates are so designed that they do not, in closing, alter the direction of the stream, but only its width, so that it continues at all times to enter the wheel at an angle of about 45° with the direction of its motion, that is, in a direction bisecting the angle between the blade and the rim.

It follows that for perfect efficiency the velocity of the stream should be $\sqrt{2}$ (1·4) of the speed of the wheel at the point of admission, which is about 170 feet per second. The theoretically best speed then for the water at admission is just over 240 feet per second.

The height of the fall being 590 metres or 1,935 feet, the free velocity due to the fall would be nearly 360 feet per second, but since the water has to flow down a long pipe of 40 centimetres diameter to enter the machine, the friction in this pipe reduces the speed at the nozzles

to a much smaller figure. This actual speed we are not in a position to estimate with any great accuracy, nevertheless we are able to trace very approximately the various losses of energy in the machine.

Thus a glance at Fig. 22 will show that the blades are inclined at 30 degrees to the rim of the wheel at the discharge end, and we can easily estimate the speed of the rim as about 188 feet per second. It follows that the least velocity in space with which the water can possibly leave the wheel is 94 feet per second, when its velocity relative to the wheel is 163 feet per second, and the energy then carried off by the water (which flows at the rate of 60 gallons a second) is $\frac{1}{2}MV^2$, or 2,650,000 foot-poundals, that is to say, 87,500 foot-pounds per second, and probably the energy of the discharged water is more than this. But the whole work done by the fall is 1,161,000 foot-pounds per second, and the useful work developed by the turbine is 1,600 H.P. (French), or 868,000 foot-pounds per second. This leaves 205,500 foot-pounds per second wasted in friction in the pipe and injector nozzles, impact at admission and friction in the wheel channels. But we must remember that all the energy represented by the motion of the water at discharge is not carried away. It will be noticed that the wheel runs in an air-tight case, and the motion of the water at discharge is converted into pressure by a diverging pipe as it emerges into the tail race, while the wheel runs in a partial vacuum.

Friction in the wheel channels is not a very large item in any impulse turbine, and it would appear on every ground that the greater part of the above loss is due to impact at admission, as the velocity of the water at admission is probably about 330 feet per second. The losses may be assigned to the following causes:

Friction in pipe and nozzles	7%
Impact at admission	9%
Friction in wheel passages	½%
Journal friction and air friction	1½%
Energy of discharge	7%
	25%
Output	75%
	100%

It is not very easy to see how much of the energy wasted before discharge is consumed in friction in the supply pipe and how much in impact on the wheel, but the supposition that the greater part of the loss is due to impact is confirmed by the behaviour of the machine at low loads, for as the gate is closed the efficiency is found to drop fairly rapidly. The action is as follows. As the flow is diminished, the speed of the water in the pipe diminishes and the effective pressure at the nozzles increases. The velocity of the water is, therefore, increased and the loss due to impact increases with it. There is also a small increase in the amount of energy carried off by the water. Now, since the whole loss of energy on a gallon of water passing through the turbine increases when causes operate which tend to diminish the loss in the pipe, while increasing that due to impact, it is fair to assume that the loss due to impact is at all times in excess of that due to friction.

It is clear that a great part of the loss due to shock might be done away by increasing the speed of rotation of the wheel to 700 R.P.M., but if this were done the amount of energy carried off by the water would inevitably be doubled.

The loss due to the speed with which the water is discharged can only be reduced by diminishing the inclination of the blade to the rim at the discharge end of the passage, but this modification, too, is attended with a certain amount of inconvenience, owing to the constriction in the width of the wheel channels, and the difficulty of securing an adequate clearance. At the same time, if we bear in mind the extraordinarily high efficiency obtained by Fourneyron with his original wheel, in which this inclination was much smaller than in most of the modern Girard turbines, it seems likely that some improvement might still be effected in the design of these latter, which are in all their details so far superior to the original machine.

CHAPTER VI.

ON REACTION TURBINES.

FOR the purpose of utilizing the power of high falls, and that more particularly in the cases where it is required to produce a slow motion of rotation, as for the direct driving of mill and factory machinery, impulse turbines, such as we have described, are the most satisfactory and efficient machines that have yet been constructed. Direct driving from water power is, however, becoming very uncommon in modern factories and works, where any large amount of power is used. The great superiority of electrical over mechanical methods of transmitting power, the small preparation and trouble involved in the installation of electric motors, and the considerable advantage in efficiency and cheapness of building and running possessed by larger over smaller prime movers, have made it more usual in modern practice to generate in one central station or power house the whole power required for the running of a large factory, and to distribute this power by electrical means to the various points at which it is consumed. This tendency to centralize the generation of power is very aptly illustrated, and the possible future developments of the policy are revealed in a striking manner, by the bills which have recently been brought before Parliament for the supply of power on a gigantic scale, and in which steam turbines play so prominent a part.

In consequence of this, now almost universal, practice, it is for the driving of dynamos that turbines are now most largely required; and, for the supply of power within a moderate distance of the source, a continuous current installation, of, say, 150 volts, is at once the simplest and the most economical. It is obviously desirable that the engine or turbine from which the power is derived should, when possible, be directly connected to the dynamo, and the objection of irregular speed, to which many engines, and particularly gas engines, are in this connection open, does not apply to turbines at all. The best speed, for a turbine which is to drive a dynamo, is, therefore, the speed at which the dynamo is intended to run, and continuous current machines are now built for speeds ranging from a minimum of 400 R.P.M., for direct coupling to steam engines, up to 4000, or even more, revolutions, for machines designed to be driven directly by Parsons and by some other high speed steam turbines. It may, however, be fairly assumed that speeds ranging from 1,000 to 1,500 revolutions per minute are the most convenient at which to drive moderate-sized dynamos of the class under consideration. For the generation of power on a large scale, polyphase multipolar dynamos much more slowly driven are generally used.

We may take it, then, that the smaller water turbines are desired to run at speeds of 1,000 R.P.M., or even more, while the larger machines should be designed for speeds diminishing as the size of the wheel increases. Further, in the great majority of cases in which water is used for the supply of power, the available fall is not a very large one; a river with considerable flow and moderate fall is a source of energy far more frequently met with than a high fall, and that even in the mountainous districts where turbines are most commonly used.

Now we have seen that impulse turbines are not at all suited for the purpose of developing high speeds of rotation from low falls, and it is clear that a very large wheel will be necessary if a large flow is to be used on the free deviation system; so that, for the purpose of driving dynamos, except under a very high fall, a reaction turbine is the most suitable.

In designing a turbine for such a purpose the following points have to be considered: (1) the diameter must be small enough to give the required speed of rotation: (2) the speed must be regular and capable of rapid automatic adjustment to variations of the load put upon the machine: (3) the wheel- and guide-passages must provide for a large flow of water, and must be capable of such modification as to diminish the flow considerably without seriously impairing the efficiency of the machine.

The first condition necessitates complete admission, that is to say, it requires that all the passages should be full throughout the motion, a condition inconsistent with the use of an impulse turbine. The second condition puts an outward flow reaction turbine out of court, for the reasons given in connection with Fourneyron's wheel, and in fact it suggests the superiority of the pure inward flow type of wheel, generally known as the Francis turbine, over machines of every other design. It must be admitted however that wheels of the mixed flow type, now very popular on the Continent, gain to some extent in compactness, and consequently in speed of rotation, what they lose in efficiency and regularity of running.

We shall probably be very near the truth in saying that the output of reaction turbines is now practically confined to two types: (1) the pure inward flow, or Francis machine, in which the water leaves the wheel passages almost radially, near the centre, and then, changing its

course, is discharged from one or both faces of the wheel according to the amount of flow and the conditions to be fulfilled, and (2) the mixed flow turbine, known by various names, in which the water is admitted at the circumference, but leaves by one or other face of the wheel, in a direction parallel to the axis, after passing through a twisted channel, formed by blades of the type illustrated in Fig. 29. The first of these machines is now preferred for large installations, but for small powers the mixed flow turbine is extremely popular, and seems to be becoming more so.

The elements which go to make up a good machine are (1) proper materials and workmanship, particularly in the bearings, (2) suitably shaped wheel channels, admitting and discharging the water at the most satisfactory points, (3) properly designed fixed distributing blades, (4) an efficient system of governing. These being given, the turbine has only to be run under proper conditions to give high efficiency and uniform speed.

To go into the details of material and construction would be to venture too far into the realm of technicalities for the present work, and we will only remark that there are two different systems of construction very commonly adopted: the American, according to which the whole rotor is cast in one piece and keyed to a steel shaft, the faces of the blades being ground afterwards; and the European, according to which the rotor is built up of forged steel plates bolted together.

It would be the height of presumption to pronounce on the relative merits of two systems, both adopted by leading engineers, and both giving eminently satisfactory results. The first has the advantage of reducing the initial cost of the turbine, whereas the second reduces the danger of flaws in the metal. Perhaps a composite

rotor, such as that of the Girard turbine shown in Fig. 22 has as far as possible the merits of both constructions.

For the sake of reducing wear, it is desirable that the wheel should be so formed that the water exerts upon it only a simple torque. A thrust along the axis is particularly to be avoided, and the hydraulic parts of the turbine should therefore be made as symmetrical as possible.

We now come to the design of the channels in the wheel, which, unlike those of impulse turbines, must be always full of water in order that the pressure at the admission end may be maintained. The pressure at the discharge end of the channels must be the pressure in the wheel case; and the diminution of pressure of the water, in passing through the wheel, may be due to either of two causes (neglecting for the moment the not inconsiderable friction of the wheel passages): (1) that the pressure is being spent in increasing the speed of flow through the wheel, or (2) that the water is moving through the wheel against some force acting on it, as when it flows inwards in spite of its own centrifugal tendency. This state of affairs is realised in the case wheel patented by James Thomson in 1850 (Fig. 24), the only water turbine type really native to this country.

For the most part, in inward and mixed flow turbines, both of these causes are brought into play to diminish the pressure of the working fluid; and the blades, which are much shorter than those of the case wheel, are so bent as to diminish the section of the channels while discharging the water in a direction opposite (or nearly so) to that of the wheel's motion.

The section of the channels can be very largely adjusted by the forms given to the two faces of the wheel, inde-

pendently of the forms of the wheel blades, so that the designer has a very free hand in shaping the blades themselves, being restricted only by the necessity of in-

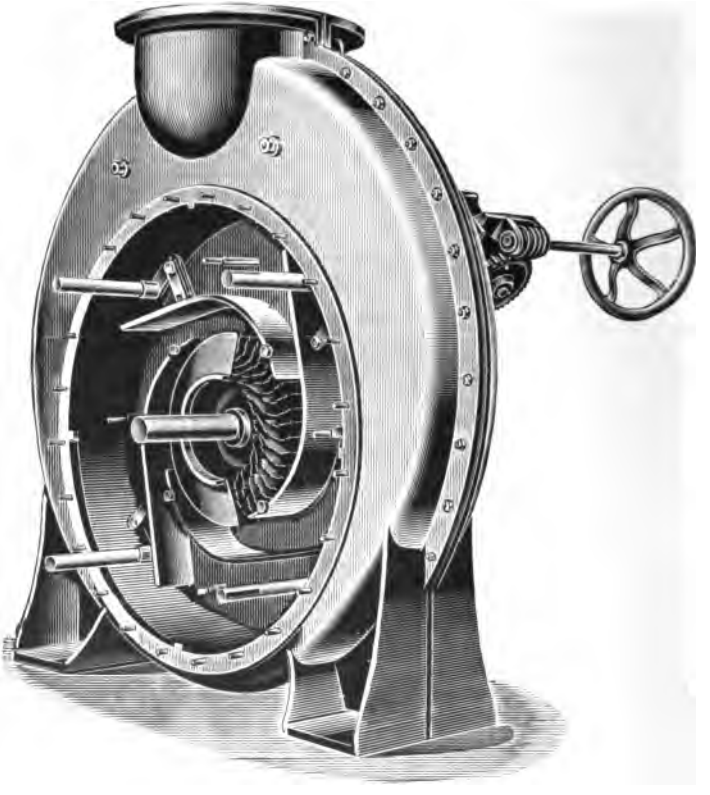

FIG. 24. VORTEX TURBINE, COVER REMOVED.
(GILBERT GILKES AND CO.)

suring that the water shall flow in a smooth curve in space, thus giving up its energy to the rotor with a certain uniform continuity essential the efficient working of the machine.

Coming now to the subject of the shape and inclination to be given to the fixed blades, we have one or two points to consider.

In discussing the subject of impulse turbines, we reached the conclusion that the direction of the distributor blades at the point of admission should bisect the angle between the direction of the wheel blades and the direction of their motion. If, however, the water is to be admitted under pressure, and without velocity along the blades, the direction of the distributor blades at admission must obviously be the direction of the wheel's motion, which is to be the only motion possessed by the water, as it leaves the guides. This is indeed very nearly the state of affairs in the case wheel of Fig. 24, but in the majority of reaction turbines this state of things is not even approximately realized, as the water is admitted at a lower pressure than in the case wheel, and with a very considerable velocity along the blades.

A reaction turbine, so called, may, therefore, be anything from a machine of the almost pure reaction type to a machine approaching very nearly to the impulse class. A reaction turbine proper is not in fact a mechanical possibility, for water obviously cannot enter the wheel without any velocity along the blades. The less the velocity of the stream along the blades, the less the flow in the machine, and when this velocity is quite abolished, the turbine, though a machine of perfect efficiency, is not working, for the simple reason that there is no water going through.

This harsh fact is the more to be lamented that we shall find numerous reasons for holding the pure reaction inward flow turbine to be the most desirable of all forms which the machine can take. But the approximation of the turbine to this form is very strictly limited by the

necessity of passing a reasonable amount of water through a wheel of moderate size.

We may take it, then, that in reaction turbines the guides are inclined to the rim at some angle less than half the inclination of the wheel blades (which would be the proper angle for the guides of an impulse turbine) an angle which is greatest when the velocity at admission is considerable, and the pressure at admission low.

What this pressure shall be is one of the first questions which the designer has to answer, for it depends very largely on the constriction of the wheel passages; if these are narrow at the discharge end, the pressure at admission must be high, and till the desired pressure is known the shape of the blades cannot be determined.

In the theoretically pure—and purely theoretical—reaction turbine, the water, being admitted without velocity relative to the wheel, must move at admission with exactly the velocity of the wheel itself, and must be subject to a pressure sufficient to produce the same velocity in the course of its passage through the wheel; it must therefore be subject to a pressure of half the head above the turbine, while moving with a velocity due to the other half, and this velocity must also be that of the wheel. In this case, therefore, the velocity of the rim must always be that due to half the head, that is, it must be 7/10 of the velocity due to the head, and this entirely without regard to the shape or direction of the wheel blades, or to the form of the wheel.

On the other hand, in impulse turbines, the speed varies very greatly with the slope of the blades, from half the speed due to the head, when the direction of the blade at admission is in line with the direction of motion, as in the Pelton wheel, to a speed far greater than that due to the head, which is obtained in some Francis

turbines with nearly flat blades, in which the water is admitted under very moderate pressure.

If then we have a turbine with blades shaped like those

FIG. 25. "VICTOR" FRANCIS ROTOR FOR HIGH FALLS.

in Fig. 25, the guide blades, whatever the pressure at admission, will never make any but a small angle with the rim. The pressure at admission will depend almost entirely on the section of the wheel channels at the dis-

charge end; if these openings are increased, the speed of the wheel will be diminished, while the torque and flow will be increased, the turbine tending to the impulse type; while a diminution in the section of the wheel passages will cause the speed to increase (the water still entering without shock, and leaving without velocity) and the flow and torque to diminish.

With blades at right angles to the rim of the wheel, as in the case wheel, the turbine will run at exactly the same speed, either as an impulse turbine, or as a pure reaction turbine, that is to say, at a rim speed of $\sqrt{\frac{1}{2}}$ or 7/10 of the velocity due to the fall. We can, therefore, in such a turbine, set the guide blades at any angle less than 45° to the rim, without affecting either the speed or the efficiency of the turbine; but the forms of the wheel channels must be such as to give a pressure at admission corresponding to the inclination of the guide blades.

The most common form of reaction turbine, however, has blades shaped like those in Fig. 26; and in these machines the guides may occupy any position intermediate between FG and HG. The effect, however, of turning the guides from FG to HG is in this case the opposite of what it was in the case illustrated above; for now, when the machine tends to the impulse type, the speed of running is very greatly increased, as well as the flow, while the torque, increasing at first, attains a maximum when the position of the guides is about HG, and would drop to a very small figure if the guide could be turned further. It is usual, therefore, to design inward flow reaction turbines with the guides inclined to the rim at some such angle as is made by KG, so that the water enters with considerable velocity, and at the same time under high pressure.

Having got the elements of the design, we can now cast the rotor and distributor in accordance therewith, and we have a turbine possessing, under the conditions for which it is designed, all the attributes that make for

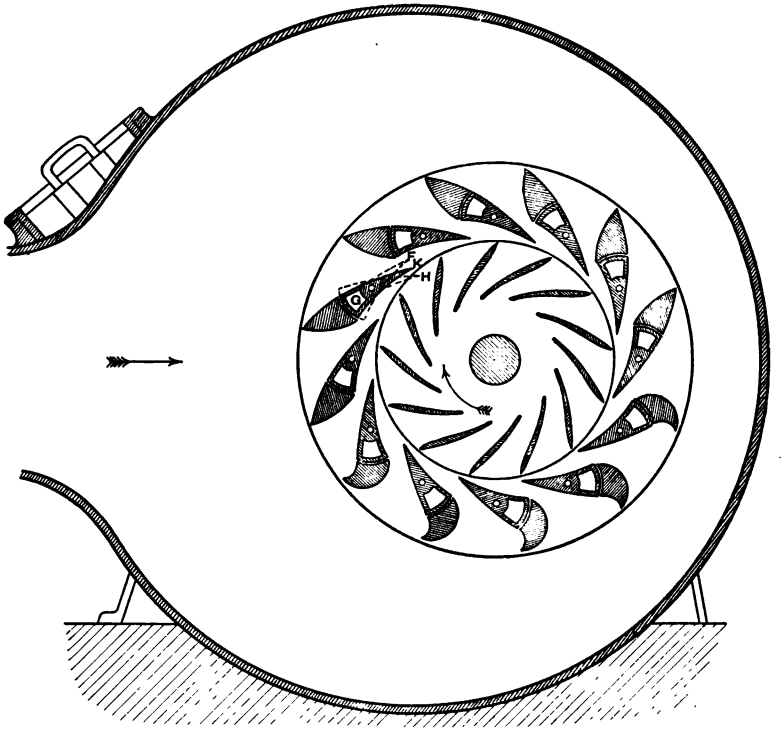

FIG. 26. FRANCIS TURBINE FOR LOW FALLS.
(PICCARD, PICTET ET CIE.)

efficiency. But he would be a poor engineer who should design a machine to run only under one set of conditions. It may be that the turbine is to run almost continually at full load, so that it is not necessary that its efficiency at low loads should be high; and in such cases it will be

sufficient to regulate it with a sluice gate in the penstock, or more advantageously in the manner of Howd's turbine, with a gate sliding on the distributor itself. Such a gate adds very little to the cost of the turbine, and, if the water supply is ample, it will suit the consumer very well to keep down first cost at the expense of efficient regulation.

This method of regulation is very far from first-class practice. In generating electric power, turbines run at ever varying loads, often very far below full load, and, if it is worth while to put in a good machine at all, it is worth while to put in one that will be a good machine all the time; that will give at half, or even at a lower load, an efficiency almost as high as under the best conditions.

In impulse turbines the only regulation necessary can be effected perfectly well by means of the injector nozzles, but the regulation of reaction turbines presents a more complicated problem, and one that has never been completely solved. For the first condition to be satisfied is that the speed of the turbine should be constant, and to avoid the carrying off of a wasteful amount of energy at discharge, this involves the condition that the velocity of discharge should also be constant; but the quantity of water in the channels is to be reduced for low loads, so that the velocity of discharge cannot be constant unless the section of the wheel passages at the discharge end can be reduced. No system of control can therefore be perfect which does not operate to some extent on the rotor blades; and no practical regulator operating on the wheel blades has ever been produced.

But, while waiting for the invention of a perfect regulator which shall control at once the wheel blades and those of the distributor, engineers have not been idle in the matter, and many excellent systems of control are now in use.

The best systems are so contrived that the wheel passages remain full throughout the motion; and in order that they may do so, no part of the orifices by which the water leaves the distributor may be blocked. Now, in order to keep the same aggregate width of orifices, while narrowing the channels in the distributor, it is necessary to alter the inclination of the guide blades; and this is commonly done. It is only at the end of the blades that any modification is necessary, and some makers prefer to obtain this, as in the Piccard Pictet turbine illustrated (Fig. 26), by swivelling the end of the guide blade while the beginning is fixed; others, as in the case wheel (Fig. 24), by turning the whole blade.

Whichever of these methods is adopted, the turning is usually effected by connecting each blade to a common frame, by a short link, so that a turn given to the frame, either by hand or by the governor, widens or closes every channel in the distributor at the same moment.

When the flow is reduced by turning the guides in this manner, the direction of flow of the water at admission is changed, and the velocity along the blades greatly reduced, while the velocity at discharge is altered in a much less degree. The consequence of this is that the pressure at admission rises, so that the total velocity at admission drops, and the machine becomes a more purely reaction turbine. It is a happy consequence of these changes that the velocity of the water in the direction of motion of the wheel is not greatly, though it must be to some extent, increased; so that, while a certain amount of shock at admission is unavoidable, it is kept within very moderate limits.

A reduction of output, then, even if obtained by the most satisfactory method yet known, is attended by an increased loss of energy carried off by the water, and an

increased shock at admission, and the problem of control must remain to a certain extent unsolved, until some mechanician is able to devise a governor capable of acting at the same time on the stationary blades of the distributor and on the rapidly moving blades of the wheel.

CHAPTER VII.

SOME INWARD FLOW TURBINES.

THERE are, as we have stated before, three classes of reaction turbines in common use at the present day, and of these at once the earliest, and in many ways the simplest, is the parallel flow, or Jonval turbine.

The design of these turbines has been very considerably modified since they originated in the simple form shown in Fig. 11; but the essential features of the old machine are still unaltered. Perhaps the most important modern improvement is the greater compactness obtained by using, when the flow is large, a number of concentric rings of fixed and movable channels, by which means the quantity of water with which the wheel can deal is greatly increased without increasing the diameter.

By multiplying the turbine in this way another advantage is obtained. In early days the Jonval turbine was regulated by a sluice valve, but when this process was condemned as inefficient the most popular system was that of closing a number of the fixed channels by sliding gates, a system attended with rather better results. Even so, however, the machine suffered under the disadvantage that the pressure in the wheel channels at admission could not be maintained, as these channels were emptied in passing the closed gates, and so when they were filled again it was with considerable shock.

With the multiple turbines, however, it is possible to cut out a whole ring of channels without in any way affecting the operation of those which remain in use, and consequently the output of the machine can be reduced with little, if any, decrease in efficiency.

Now each ring of channels in the turbine is moving faster than the ring inside it, and slower than the one outside, while the water pressure acting on each ring is the same, so that if all the blades are to do their duty faithfully they must not be all of the same shape; in fact, while the blades in the inner ring are very much curved so that the direction of the water is reversed as it flows past them, as in a Pelton wheel, the blades in the outer ring will be very much flatter and will be set very obliquely to the axis as in a screw propeller. So also the forms of the fixed, or distributor, blades will be very different in the inner and outer ring, being designed to inject the water, in the first case, in a direction only slightly inclined to the direction of motion, while at the outside of the wheel the water is to enter more in the direction of the axis and to press on the flatter blades as they move rapidly past.

The variation in the set of the moving blades can be seen in the accompanying figure, which represents the rotor of a Jonval turbine of moderate power for use in connection with a large flow and small head. The bottom of the head race consists to all intents and purposes of a large sieve, which imparts a screw motion to the water as it passes through, and this motion is given up to the fan-like runner which confronts the stream at the end of its passage through the distributing channels. So in the modern Jonval turbines we have got back nearly to the old fan set in the bottom of the head race, which Belidor described in 1737; but with this difference, that the water

is given a screw motion before it meets the runner, and so is able to issue therefrom without the whirl which was at the same time essential to the working of the Basacle reaction wheel and fatal to its efficiency. The Jonval

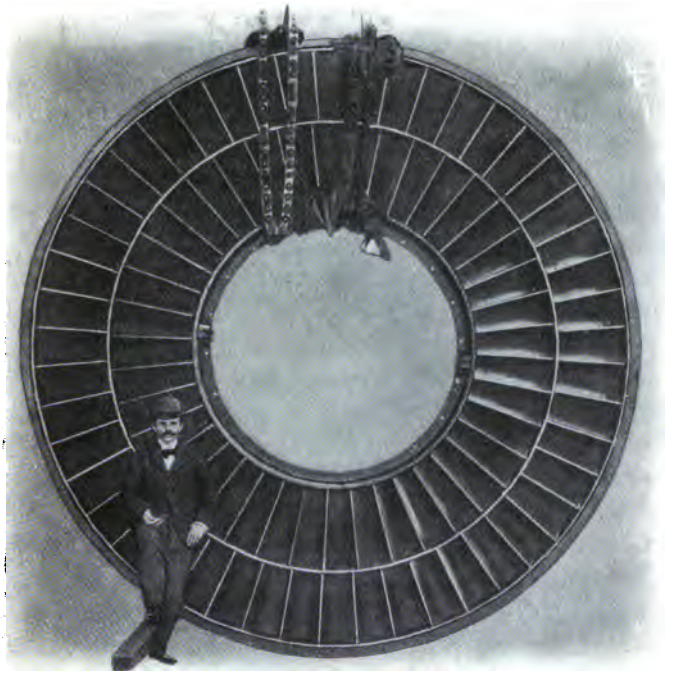

FIG. 27. RUNNER OF JONVAL TURBINE, 40 H.P. UNDER HEAD 2 FEET (ESCHER WYSS AND CO.).

wheel can, theoretically at any rate, like all other turbines, develop power with perfect efficiency.

The Jonval turbine, however, has now for some time ceded the premier position among reaction turbines to those with external admission only, and in the discussion

of modern machines it is to these, the inward and mixed flow turbines, that we must devote the greater part of our attention.

We have already mentioned Howd's turbine (Fig. 14), which had in earlier days a great reputation among New England farmers and others, who desired to make use of unlimited water in a convenient, but not necessarily efficient, manner. Howd's turbine was indeed, thanks to its cheapness and simplicity, well known to power users of that class for many years before it was taken up and scientifically treated by Francis in the Lowell experiments. Francis, reviewing his work in 1849, mentions some of the advantages of the inward flow machine, but remarks that a great increase in efficiency must be made before it can compare with the Fourneyron turbine in economy of working.

This increase was effected by James Thomson's invention of 1850 (Fig. 24)—an invention which first put the inward flow turbine into the field of scientific engineering—and was effected in great part by increasing the length of the blades, and introducing adjustable guides. By these means the inventor claimed to secure, and unquestionably did, in fact, secure, an increased efficiency at full load, a more economical system of control, and an almost perfect regularity of motion.

Fig. 24 represents a case wheel as made by Gilbert Gilkes and Co., of Kendal, who have developed the native British turbine with a great deal of success. One side of the case is removed, and one half of the wheel cover, so that it is possible to follow the path of the water, from its entrance into the case at the top, between the movable guide blades, and into the wheel. From this the water is discharged near the hub, and then pours out of the case in an axial direction, by the pipes shown in Fig. 28.

The larger turbines are built symmetrically, and the water leaves by two pipes in opposite directions, but in many of the smaller machines the water is discharged only from the lower end of the axis, which is then set vertically, so that the weight of the wheel to some extent compensates the upward pressure of the water.

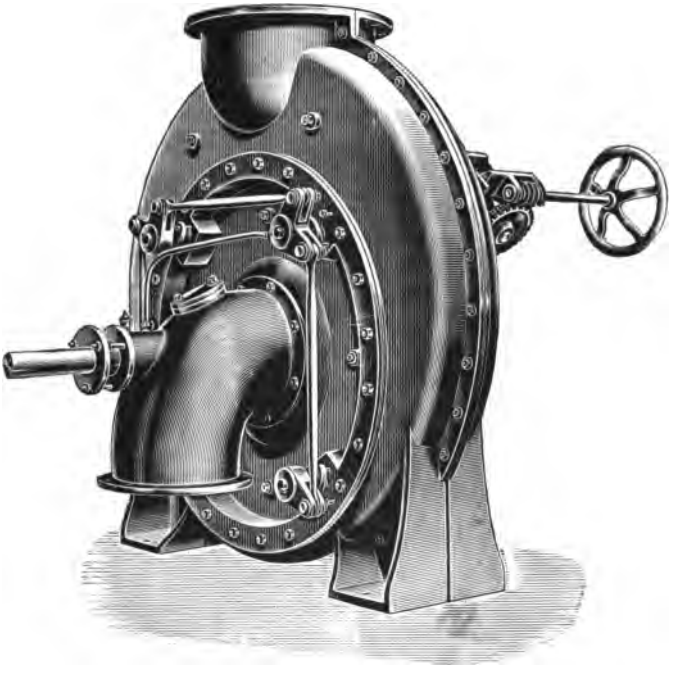

FIG. 28. VORTEX TURBINE, COVER REPLACED.

The spiral guide blades are four or six in number, according to the size of the wheel, forged of steel, pivoted on pins near to their ends, and adjusted by the connecting rods and cranks, which can be seen in Fig. 24 keyed on to the long shafts projecting from the front of the case. These shafts are connected, as shown in Fig. 28, so that

every adjustment takes effect equally on all the guides. The blades of the wheel are also forged, with lugs on their edges, which are riveted through the crown plates, so that the blades are not susceptible of any adjustment.

When the turbine is working normally under full load the speed of the rim is that due to half the head, namely, $\sqrt{GH}$ feet per second, and the water enters the wheel with this velocity, at a pressure of half the head. This pressure is spent to a certain extent in developing the required velocity of discharge (the velocity of the inner rim of the wheel), but to a much greater extent in overcoming the outward pressure of the great weight of rotating water in the wheel; a pressure proportional, as we have seen, to the square of the speed of rotation. The turbine is driven like the old turbines of the Garonne by a forced vortex in which the blades are placed, but with this difference, that in the old turbine the wheel was in the vortex, while, in the new one, the vortex is in the wheel; in the old turbine, too, as in Burdin's turbine, the action of gravity on the water took place while it was in contact with the blades, necessitating a rotor of enormous size, whereas in the modern wheel gravity does its work in the supply pipe.

Now, if by fluctuation of the load on the turbine the speed is momentarily increased, the pressure at the circumference increases as the square of the speed, and, as it increases, the velocity of the water at admission drops, with the twofold effect, that the flow is diminished, and that there is a shock on the backs of the blades as they meet the water, so that the original speed of the wheel is very quickly restored. If, on the other hand, an increased load reduces the speed of the wheel for an instant, the flow is immediately increased, and this greater volume of water enters the wheel with a shock due not only to

its own increased velocity, but also to the diminished speed of the blades themselves; and this shock, objectionable as it may be from the point of view of the seeker after efficiency, causes a large torque, and so ensures the stability of the motion.

Even without attention, then, the case wheel may be trusted to maintain a fairly uniform speed, and may for this reason be run without a governor, a saving both in first cost and in the expense of upkeep; but if the turbine is to run at low load for any length of time, the conscientious engineer will not tolerate either the slightly increased speed, or the loss by impact, involved in the automatic regulation.

For this reason the guides are hinged, and may be adjusted by turning a hand wheel so that their outer ends are shut down on to the wheel, narrowing the channels of the distributor, and reducing the flow; and this regulation can be effected with far less loss of efficiency than in any of the turbines of the more impulsive type, for two reasons. Firstly, because a slight alteration of the direction of the blades is sufficient to close the channels as required, so that the velocity of the water relative to the wheel at admission is unaffected; and secondly, because, though the velocity of discharge must of necessity be somewhat diminished, the said velocity is always so small that this is not a serious matter. For these two reasons, regulation by the guide blades does not perceptibly affect the pressure, or (consequently) the velocity, at admission, so that the water still enters without shock, and leaves with very little motion.

We have dilated at some length on the merits and beauties of the vortex turbine, as the modern case-wheel is called, and probably there is no machine calculated to rouse so much artistic enthusiasm in the breast of an

engineer; but, like all things earthly, it has its limitations; and its most serious limitation is this: that the slow speed at which the water enters the wheel requires a very large wheel to allow sufficient flow for the development of much power, particularly from a low fall; and the length of the blades, which is an essential feature of the design, implies a heavy wheel, containing while in motion a great weight of water. But a more serious inconvenience results from the size of the wheel. The speed of the rim is in every case the free velocity due to half the head, so that the speed of the rim under a head of 50 feet would be 40 feet per second, and the speed of rotation of a wheel of 2 feet diameter, capable of developing 50 H.P., with a flow of about 4,000 gallons a minute, would be not more than 382 revolutions per minute—too slow a speed for running a dynamo.

Now, as a wheel of some size is an absolute necessity, the speed of rotation of a vortex turbine under a given fall is very strictly limited, while the weight of the rotor restricts less rigidly the greatest power that is by any means obtainable from this type of machine. For very large powers and for very low falls we have recourse to turbines of the Francis and mixed flow classes; but for such purposes as lighting and power supply for a country house or farm, under a head of 50 to 200 feet, the vortex turbine is probably the best, as it is certainly the simplest, machine that has ever been produced.

Many of the features of the vortex wheel will be found in all external admission turbines, as, for instance, the movable guides by means of which the flow is regulated in all the larger and more elaborate machines, but the features which render the case wheel unsuitable for very high powers or very low falls have in some of the other machines been abolished. Thus it is usual in a Francis

turbine to find the guides inclined (as in Fig. 26) at a considerable angle to the rim of the wheel, so that the flow is large even through a small runner. To facilitate a still larger flow, the blades are made very wide; but, of course, this means that it is no longer possible to maintain a large channel at discharge by giving a conical form to the crown plates, and so it is not possible to carry the blades very far towards the centre, where they would approach each other too closely. Short blades are therefore used, so that there is not a great deal of water in the wheel when in motion, and the bearings are therefore subject to less strain than in Thomson's wheel. On the other hand there is not the same mass of water to exert centrifugal force, in order to regulate the speed, and steadiness of motion is to some extent sacrificed.

The problem of control also becomes more difficult than before, as, in order to narrow the distributor passages, it is necessary to alter the inclination of the guide blades, thereby causing a certain amount of shock at admission. The losses due to this cause are, however, small.

The general construction of the Francis runner is not at all unlike that of the Girard. The crown (Fig. 25) is cylindrical in form, and so like the crown of the Girard wheel, shown in Fig. 21, that one might almost be taken for the other at first sight. The wheels, too, are built up in very much the same way; the crown being connected to the hub by a conical or curved web, which forms one face of the wheel, and serves to deflect the water as it issues from the channels, so that it leaves the machine axially. The pressure of the water on this web exerts considerable thrust along the shaft of the turbine, but this is now balanced by the way in which the turbine is set.

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We have claimed for Francis turbines that they are able to deal with a very large flow of water in a very small wheel, as water is admitted with considerable velocity relative to the rotor; but the real difficulty of dealing with large quantities lies not in the admission, but in the discharge. The water, if discharged near the shaft, leaves with but little velocity, and wherever discharged, it must leave at a small angle with the surface, so that it is necessary that the surface from which discharge takes place should be of considerable extent.

It is found in the Francis turbine that the internal surface of the cylindrical crown is inadequate for the discharge; as the water flows inwards its motion is to be retarded, and it is necessary that some should escape from the channels to make this possible. For this reason the crown is built with only one face, so that some of the water can escape from the bottom of the blades while the rest flows inwards; but the energy of the former is not wasted, for, though its path in the wheel is very short, it is also very crooked, and the water leaves in a direction opposed to that of the wheel's motion, practically without velocity. These are the reasons for the form of the Francis runner shown in Fig. 25, and for high falls it would be hard to beat.

The Francis turbine, in fact, is decidedly the best for large installations, and it holds the market at present. The 10,000 H.P. Francis turbine erected by Escher Wyss & Co. at Niagara, is probably the most powerful hydraulic engine ever constructed.

For other conditions other types of runner are necessary. The wheel shown in Fig. 25 has a rim speed of little more than half the free velocity due to the fall, and would therefore be very suitable for driving a dynamo under a head of 60 to 200 feet; the wheel in Fig. 26 on

the other hand, is designed to run under a head of less than 60 feet, and has a peripheral velocity about twice that due to the fall, so that it, too, is well suited for electrical work, its normal speed being 490 R.P.M.

Mixed Flow Turbines.

The elements of design which have rendered the compact inward flow turbine capable of developing such enormous power, are present in a still higher degree in the remaining wheel that we have to consider.

The conditions that confront the manufacturer of turbines for use in this country are the absence of high falls, combined generally with copious water supply, and the necessity in many cases of running at speeds sufficient for electric generation.

High efficiency is no longer the *summum bonum*. What is wanted is a turbine that will run steadily, utilize a large flow, and that with a moderate peripheral speed, and high speed of rotation.

The first condition is to a large extent secured by using external admission only; the second requires that the action should be very different from that in the "pure reaction" type of machine. Now if the blades are made as flat as is consistent with the absence of shock at admission, and inclined at a moderate angle, say 35°, to the rim, it is possible to secure a peripheral speed of about twice the free velocity due to the fall, or about 26½ feet per second on a 6 foot fall; and, given that fall, this is about the highest speed attainable. Now if we wish to couple directly to a dynamo, we want a speed of rotation of about 500 R.P.M., so that we must have a wheel of

only 1 foot diameter, while, reckoning on 70 per cent. efficiency, the flow must be 13 gallons per second per horse-power.

The water enters, as we have said, at a considerable angle with the surface of the wheel, and, if we make the

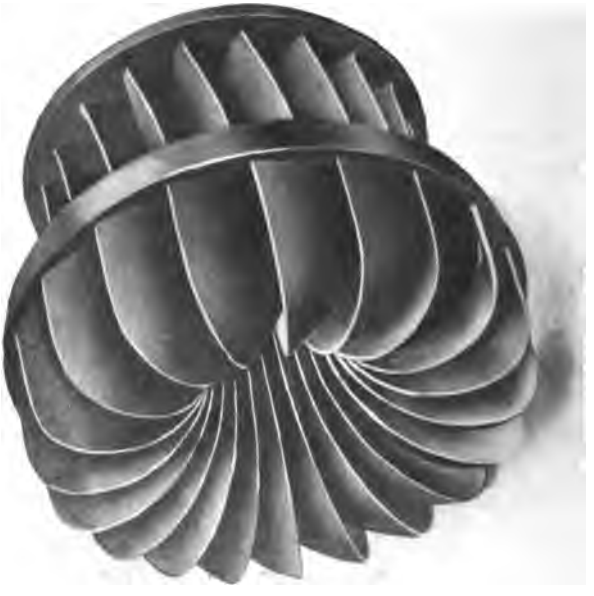

FIG. 29. "VICTOR" MIXED FLOW ROTOR.

barrel of some length, there need be no difficulty about letting enough into the wheel for quite a large power, but since it must leave at a small inclination to the surface of the rotor, the discharge may present some difficulty; at any rate, the surface of discharge must be much larger than the surface of admission, and yet the water has to attain the discharge end of the channel by

flowing in a smooth curve, and, so far as possible, by inward flow towards the shaft.

How this result has been attained is very strikingly illustrated by the mixed flow rotor shown in Fig. 29. A very large development of the sidelong discharge of the Francis turbine has taken place, and the water now leaves not only inwards and axially, but even outwards, almost from the surface by which it entered. The greater part of the water in mixed flow turbines leaves axially; it is important to keep the amount of water discharged outwards within very moderate limits, lest the effect of centrifugal force on that water should cause the machine to experience the disadvantage of unstable running common to all outward flow reaction turbines.

In a mixed flow turbine, such as we have described, all the water enters the rotor at the same pressure and velocity, but the pressure of that part of the water which is discharged from the inner edges of the blades is used up in overcoming its centrifugal tendency, while that of the water discharged from the outward facing edges goes to accelerate the flow. It follows that if we examine the motion of the water as it is discharged from the long edge of one of the blades, we find it everywhere of the same pressure, but moving at a higher and higher speed as we follow the edge away from the centre of the wheel, and, as the speed of discharge gets higher, the aperture between the blades gets narrower.

It might be possible to investigate very fully all the different sources of loss in connection with this machine and to criticize it with more or less justice on the subject of its efficiency; the fact is that this turbine was never designed to satisfy a theoretical standard of performance, but to meet a very real need for a turbine that should be capable of developing considerable power at

high speed under a fall of a few feet, and so well has it met this need, that there are turbines on the market at the present day, which, with a rotor of 9 inches diameter, will develope 2 H.P. under a 6 feet fall, at speeds of

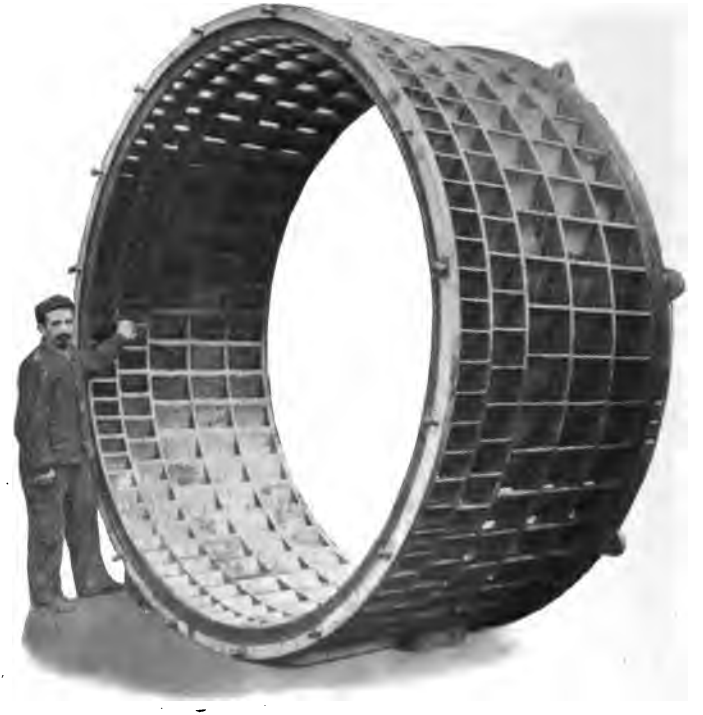

FIG. 30. DISTRIBUTOR FOR CYLINDER GATE TURBINE.
(PICCARD PICTET ET CIE.)

from 300 to 400 R.P.M.; and that with an efficiency of something like 75%.

The efficiency of these turbines may, then, be very high. This is the machine used above all others by the average miller, and there are probably more of them in use in the world at the present day than of all

the other turbines put together, though it may well be that the aggregate power of the Francis machines would exceed theirs. This wide use among small power consumers, who have often a great flow of water at their disposal, renders initial cheapness a more important attribute than economy of regulation, and, for the sake of cheapness, this regulation is generally effected by a gate sliding on the outside or inside of the distributing cylinder. The latter type of gate has the advantage that the water cannot spread out in the distributor and lose speed after passing the gate; on the other hand, the inner gate changes the direction of the stream entering the rotor as it is shut down.

When gates of either of these types are used, the stream will naturally spread on entering the rotor, so that it is not easy to keep up the pressure at admission, and the chief loss of efficiency arises from this source. The reader may remember that this difficulty was overcome in the case of the Jonval turbine by the use of a number of concentric rings of channels in the rotor, of which one or more could be cut out of action by the gate; a similar system has been employed with some success both in inward and mixed flow turbines, the different rings of admission ports being situated one above the other up the barrel of the rotor; but in the mixed flow wheel, owing partly to difficulties of manufacture, and partly to the desirability of allowing the water to adjust its own curves of motion (particularly at full load) by passing from one channel into the next, the different rings are not entirely divided, each full-load channel being fitted with partitions which do not entirely fill it. Similar partitions are often fitted in the rotors of turbines not so controlled (Fig. 31).

When an internal gate has exactly reached one

of the partitions, the sections in use are full, and the turbine will run almost as efficiently as at full load, but such high efficiency cannot be expected when one of the sections is partly gated, and so using water at lower pressure than do the other sections.

The cylinder gate is not very far behind the more complicated regulators in efficiency, and it is much cheaper to construct, so that it both is, and will probably continue to be, the most popular among the small users for whom mixed flow turbines are principally designed.

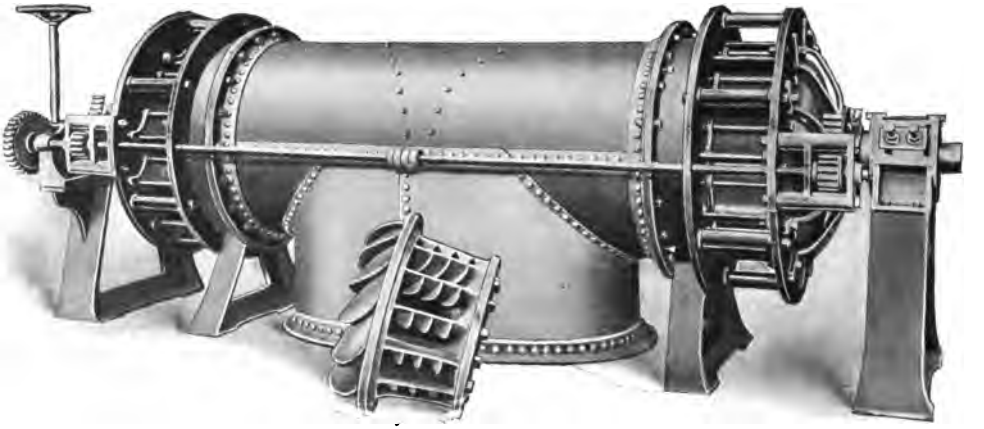

FIG. 31. DOUBLE TURBINE SET.
(GILBERT GILKES AND CO.)

CHAPTER VIII.

ERECTION AND CONTROL.

THE problem of erection, which is so complicated in the case of the reciprocating steam or oil engine, and which has given rise in this connection to endless litigation, is vastly simplified in the case of water and steam turbines by the absence of the vibration which requires heavy foundations and massy bedplates for all machines with reciprocating parts.

In the early days of the art it was much debated whether a turbine ought to be set above or below the tail water. If the first arrangement were adopted, a part of the head above the wheel was necessarily sacrificed; and if the second, difficulties as to clearance and back pressure were inevitable. It has now become the custom to set reaction turbines, in a manner introduced by Jonval, at the head of a short suction pipe leading down into the tail race; this ensures that water leaving the wheel will flow down the pipe and out of the way as quickly as possible, and at the same time secures that the difference of pressure between the admission and discharge ends of the machine shall be the full difference due to the head.

But this is not the only advantage obtained by the use of a suction tube, for it is an occasional, and might with advantage be a very common, practice to form this tube of a small section near the turbine, giving it a flare

as it enters the water. The water leaves the turbine, however well designed, with a certain speed, and so enters the tube, but as the section of the tube increases, the motion of the water is retarded, and its pressure consequently increased. Thus the difference in pressure between the two ends of the pipe is more than that caused by its length, and the kinetic energy of the discharged water is not entirely wasted.

Further, the suction along the shaft, exerted on the rotor by the water in the tube, balances the pressure of the water on the conical face, and so does away with thrust on the bearings. To secure that all such thrust is accurately neutralized, it is now a common practice to mount reaction turbines in pairs on the same axis (Fig. 31).

The smaller machines, particularly those for use in connection with the low falls available on the Thames and other English rivers, are supplied by the manufacturers in a compact form, requiring nothing but a resting place, a supply of water to the outside of the case, and a channel to conduct the discharged fluid from the base of the turbine. These wheels are now almost invariably mounted at the top of suction tubes, and only just below the surface, of the head water, and the operation of mounting is somewhat as follows.

A floor is constructed over the tail race, and on a level with the bottom of the head water; this floor may be carried by brickwork arches, steel joists, or wooden beams, according to the weight of machinery to be erected. Water is admitted to the floor by a large sluice, which is closed when it is necessary to get at the turbines for repairs, and it is carried down into the tail race by pipes of an inverted funnel shape, which it enters by holes in the floor. To erect a turbine all that is necessary is to

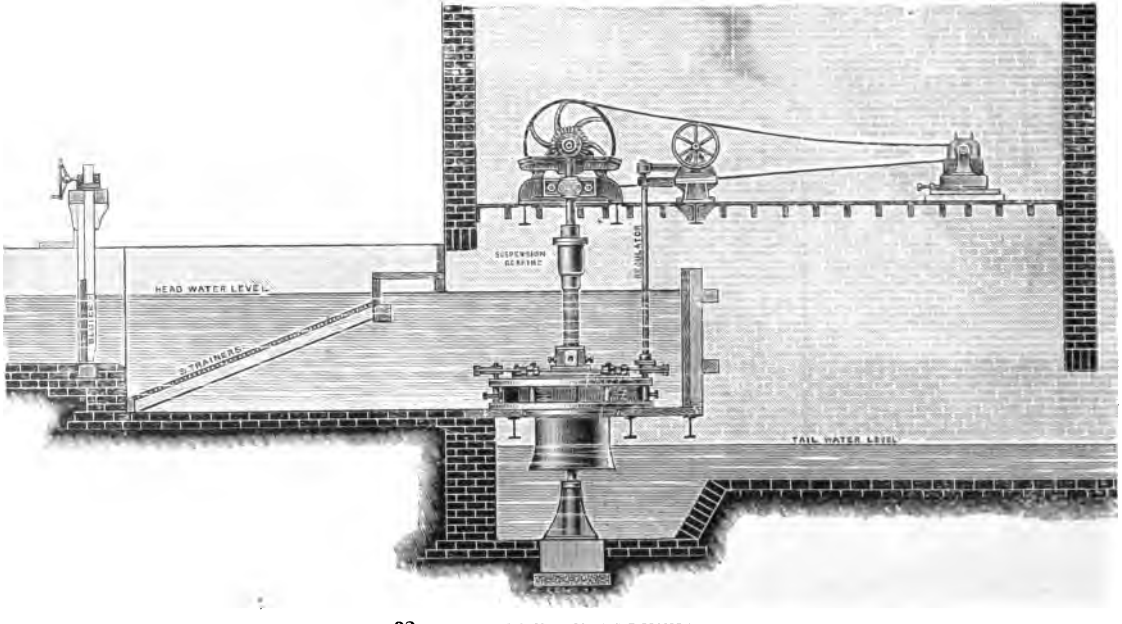

FIG. 32. VORTEX TURBINE DRIVING A MILL.
(GILBERT GILKES AND CO.)

seat it on the floor above the mouth of the suction pipe, just as the vortex turbine is seen placed in the illustration (Fig. 32); even the bolts used for its better securing are not a necessity.

The larger machines, however, are treated with the respect which they deserve, and are not infrequently built into great flumes of masonry at enormous expense. In other cases the water is conducted down iron pipes to the turbine, and these supply pipes are in turn surrounded by a well of brickwork giving access to the machine. It must be borne in mind that as one of the principal uses of turbines is for direct coupling to dynamos, which naturally are situated in a power house directly above the turbine itself, the latter must be underground, and, therefore, when high falls are to be used, the construction of elaborate wheelpits, such as those shown in the illustration of Messrs. Escher Wyss and Co.'s installation at Niagara, is one of the features of the undertaking. For the development of power under very high falls it is common to use machines with horizontal axes, like the Girard turbines at Gurtnellen, and the power house is then situate at the base of the fall, the penstock being in the open; or, if machines with vertical axes are used for very high falls, they are surrounded by a steel case, into which the water enters at the side, while the shaft pierces the top of the case.

The solution of all these problems of erection depends, perhaps even more than does the design of the turbine itself, on the local conditions; thus, though flumes of brickwork may suffice to carry the water to a turbine set under a low fall, a steel pipe is necessary to withstand the pressure of a high head. Now, to withstand a given pressure it is necessary that the thickness of a pipe should be proportional to its diameter, so that the

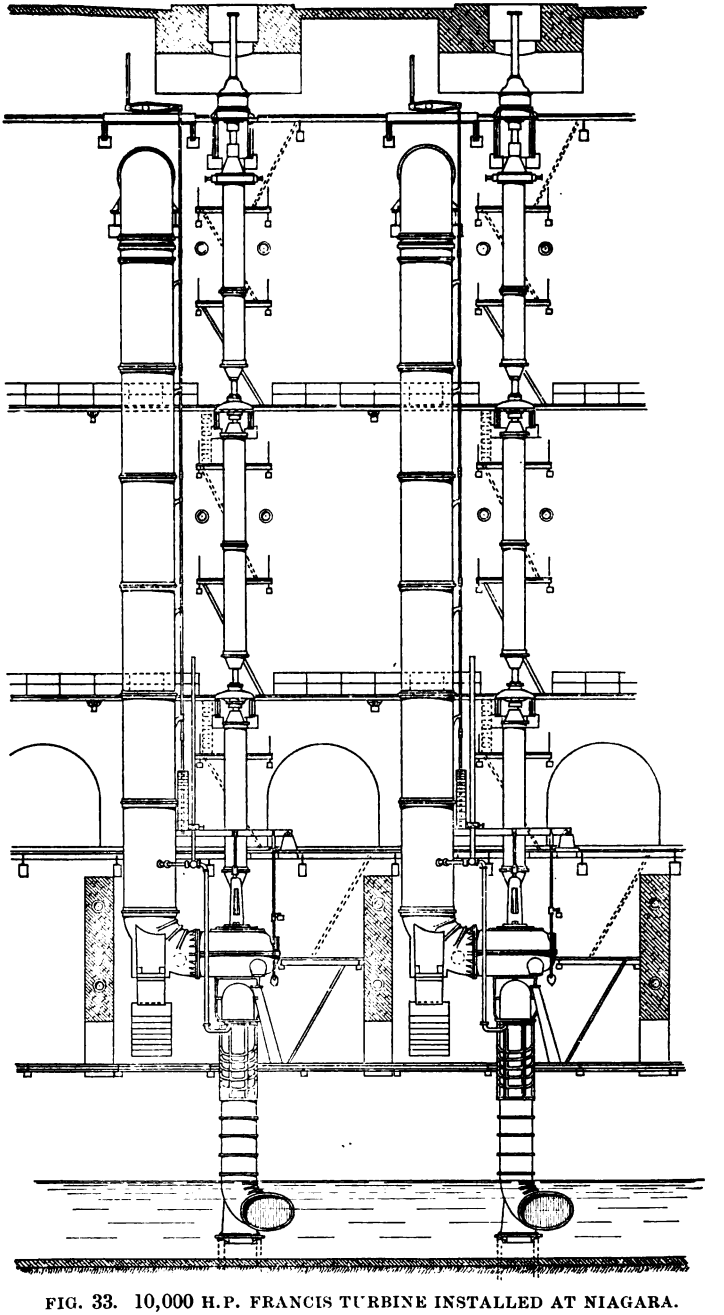

FIG. 33. 10,000 H.P. FRANCIS TURBINE INSTALLED AT NIAGARA.
(ESCHER WYSS AND CO.)

amount of metal in it varies as the square of the diameter, and the cost of a large pipe is therefore an important consideration. So is the loss of head by friction in the pipe, and as this loss is proportional to its length, and inversely proportional to fifth power of its diameter, it is important that the consideration of first cost should not lead us to economize unduly in the section.

We can, however, save both in first cost and in economy by making the pipe as short as possible, and, for a given head, this object is of course to be obtained by making it as nearly vertical as may be.

The only two rules, then, that can be confidently given for the installation of every turbine are:—that it should be situate directly above the tail race at a height of not more than 25 feet, that the lower part of the penstock should be vertical, and that, at any rate where very large and heavy rotors are used, the power house should be situate at a short distance directly above the machine, so that the dynamo armatures may be keyed or pressed on to the shafts of the turbines.

* * * * *

The operation of the turbines is generally controlled from the power house, when they are used for driving dynamos, or, in mills, from the floor immediately above that on which the turbines are situate. If it is required to run the wheel at low load, it is always possible to effect by hand the necessary regulation of the sluice, guide blades, or nozzle, by which the flow is regulated; but the construction of even the largest turbines is so simple, and their running so smooth, that it is an unnecessary expense and trouble to have a man always on the spot to look after them, and it is therefore very desirable to render them self-governing.

Two properties are required of a governor:—that it should act with the greatest promptitude in the case of any serious divergence from the normal speed, and that it should be sensitive and powerful enough to keep the speed appreciably constant.

Now, whether it is a steam engine, a water turbine, or any other form of prime mover that we are controlling, it is not easy to combine these two properties in one governor. A governor which is to adjust the gate or blades with extreme accuracy must move it slowly into position, and this is inconsistent with prompt action. A governor, too, which is to satisfy the first condition must act directly on the gate; but if it is to do this, serious difficulties will be found in the way of constructing it, so that it may control a heavy gate or the numerous bearings of adjustable guide blades, when the variation of speed is so small as 1 in 300.

Nearly, if not quite, all mechanical governors act on the centrifugal principle; that is to say, the controlling force is derived from the tendency of two weights, carried on a spindle in gear with the rotor, to fly outwards. When the wheel is running at normal speed, this outward tendency is exactly balanced by springs, which may be adjusted by hand to any required speed. If the speed of the machine be at all increased, the weights move out, stretching the springs. But, obviously, the force which these weights exert is proportional to the variation of speed, so that they are rather ineffective when this variation is slight; also, this governor can only act powerfully if the radius of motion of the balls is rather a large one; and then they have a tendency to hunt, or sway out and in, which would make the motion very unsteady, if they were not so controlled as to act only under strong provocation in the form of a variation of speed.

For these reasons it is now usual to fit the larger machines with two governors, of which one acts promptly, generally on the gate, while the other acts slowly on the nozzle or guides, with great delicacy and power.

Of this governor prompt action is not required, so that it may go to work by a roundabout way; but it must act with extreme delicacy, and with great power, however slight the variation from the normal speed. In constructing a governor of this sort we do not, therefore, have recourse to the actual centrifugal action of the weights for the power required to move the gate or blades, but we make this force unlock the door by which a far more powerful agent comes into play.

There are a number of mechanical devices by means of which this is effected. In one, very commonly used on steam engines, the governor operates by throwing into gear cog-wheels through which the regulating valves are driven from the shaft of the engine. A device more commonly found in turbines connects the governor directly to a small slide valve, through which the steam or water is admitted from the boiler or head to a small piston; and by means of this the admission valve is operated.

The distinguishing feature of both these mechanisms is the fact that the heavy work necessary to regulate the flow is performed directly by the working fluid, so that the governor has a duty requiring very little mechanical force, and it can therefore be constructed in such a fashion as to act with extreme delicacy; also its action is very powerful, even when the variation from the normal speed is slight.

Fig. 34 shows a governor of this last type as applied to a Pelton wheel. The flow in these wheels is regulated by the extrusion of a needle through the con-

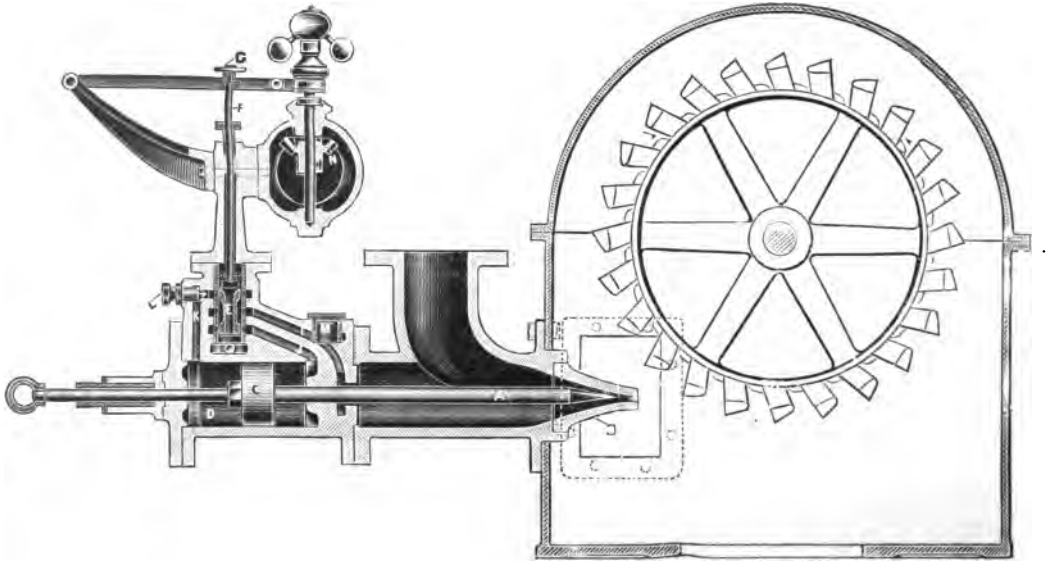

FIG. 34. PELTON WHEEL GOVERNOR.
(GILBERT GILKES AND CO.)

verging nozzle, so that speed, direction and line of action of the stream are unaltered—this causes the very high efficiency of these wheels at low load—and the needle is operated either by hand or by a piston on the same shaft. The figure shows the piston C sliding in a small cylinder to which water is admitted, on either side of the piston, by the motion of the slide valve E, controlled directly by the governor.

This gives a delicate and efficient control, but by no means a rapid one, so the nozzles are also set on a ball and socket joint, which allows them to be deflected, in the case of a sudden rise of speed, and the water is then thrown clear of the bucket. Of course this involves a waste of energy, but, in emergency, efficiency must at times be sacrificed.

One more point requires mention. It does not often fall to the lot of an engineer to erect plants in England under a high head, but when such a head is used, he must bear in mind that while the turbine is running there is a flow of water throughout the entire length of the penstock, and when the admission is reduced or shut down, the whole moving mass of water is checked, so that a shock like that in a hydraulic ram acts on the base of the penstock, and in a less degree on its whole length. The flow must therefore be checked very slowly; and yet the action on the wheel must at times be very quickly stopped. We have to check the action therefore, either, as is done in the Pelton wheel, by diverting the stream, and allowing it to run to waste; or, in a rather more economical fashion, by the introduction of a sort of buffer, which takes the form of a reservoir of compressed air in permanent connection with the base of the penstock. Into this the water rushes, when suddenly debarred from the turbine, and it continues to fill this reservoir,

against a rising air pressure, until the motion of the column of water behind has slowed down. Then the air begins to recover, and forces the water out of the reservoir again, either through the turbine or back to the head, so that none of the energy is finally lost to the machine. If this device is used, the only danger is that the steady increase of pressure in the reservoir may be too much for it, or for the supply pipe, before the flow is checked, and it is therefore necessary to provide a reservoir of volume proportional to the section of the penstock and to the square of the speed of flow in it at full load. Of course, in some of the machines which we have described, such a reservoir would be extremely difficult to construct, and the compressed air inside, under a head of 800 or 900 feet of water, would be a fruitful source of danger, so that in such cases we must either combine with it the deflecting nozzle, or else rest satisfied with a slow cut off for the turbine.

Such are, in brief, the solved and unsolved problems presented by the installation of water turbines, a branch of engineering enterprise not yet fully worked out, and a science not yet perfected, offering at once the simplest of all prime movers to the user of natural power, and at the same time affording some of the prettiest of problems to the expert engineer.

PART II

STEAM TURBINES

CHAPTER I.

THE STEAM ENGINE.

WHEN Humphrey Potter, in 1713, devised automatic steam valves for use in connection with a pumping engine, the engineers of his time were prompt to recognize the truth that this step was the first and most difficult one in a great advance in the arts of civilization; but they failed to perceive the further truth, which indeed we have only begun to discern at the present day, that this was not a step in the direction of the true and natural development of the steam engine, but, on the contrary, one which was to postpone that development for a hundred years, while the minds of men wandered in the paths that the inventor had laid open.

Hero of Syracuse and Giovanni Branca had used the pressure of steam escaping from a boiler to drive a wheel, and, familiar as we are with the high pressure boilers in use at the present day, it seems almost incredible that the engineers of the eighteenth century were in the habit of using steam to operate a piston not by pressure at all, but by suction. Yet this was in fact the case.

At the time to which we refer, steam was not used to produce rotation. The crank, an essential part of the rotary-reciprocating mechanisms which are common to-day in so many forms, was not yet invented. The purpose for which steam was used was that of pumping,

and the reciprocating pump, a very old mechanism, required a reciprocating motion to drive it, and naturally suggested the steam cylinder and piston, which was well adapted for the purpose. If we notice what was at this time the desired object, it becomes clearer to us why the reciprocating engine, ill-adapted as it is for the production of rotary motion, was the first, and for a long time the only successful, steam engine. In these early pumping

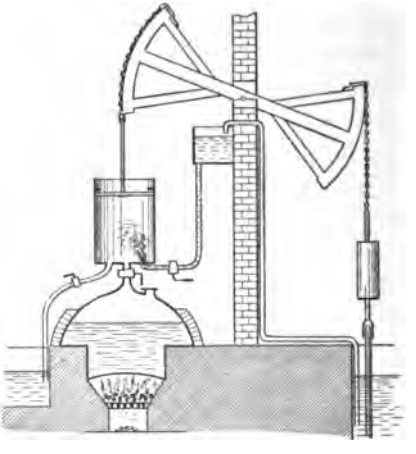

FIG. 35. PUMPING ENGINE (1710).

engines, steam was admitted to the bottom of the cylinder at atmospheric pressure. The weight of the pump rod drew the piston up, and the steam was then condensed, forming a partial vacuum below the piston, which was thus forced downwards by the pressure of the air above it. As a matter of fact, atmospheric pressure at admission was not the invariable rule, and before the time of Watt it became customary to use a double acting engine with a higher pressure.

Now the invention of the automatic steam valve made

all the difference to this engine, and it was already popular when Watt took it in hand; for it was the one kind of heat engine that would really go by itself. Watt's improvements raised the reciprocating engine almost to its present day level. He observed, and he applied in his inventions, the following principles: (1) that the pressure to which the steam could be raised by heating was just as important as (indeed, more so than) the vacuum which could be produced by cooling it; (2) that the energy of the steam required careful husbanding; and (3) that the steam engine might be applied to several other purposes than that of pumping out Cornish tin mines.

The steam that Watt turned into his cylinder was a valuable product; it cost money to produce, and was able to do a good deal of work when properly treated. The inventor did not see any advantage in wasting half its heat to warm up a metal cylinder, which had been cooled in condensing the steam during the previous stroke; he therefore stated, in his celebrated patent specification of 1769, the principle that the working cylinder should be maintained, so far as possible, at a uniform temperature; a principle which it has not been possible to carry out in any engine in which the work is done by steam remaining in contact with the containing vessel during the operation, but to which an approximation is made in compound, triple and quadruple expansion engines.

Thus an efficient engine was created, and it was soon applied to produce rotary motion by means of a connecting rod driving a shaft by gear wheels or a crank. From that time the advance of steam power was rapid, until it reached what was long thought to be its highest development, in the locomotive engine of George Stephenson, who has been so often called the inventor of the steam engine. *Tempora mutantur.* We are already faced by the

possibility that the locomotive steam engine may be superseded by the electric motor, but steam power is almost as essential a factor in engineering enterprises as heretofore.

So a machine, designed for the purpose of producing a purely reciprocating motion, came to be the accepted prime mover for the production of rotation; and for a century never an engineer dared to devise a steam engine, but he so clothed it with valves and links and reciprocating mechanisms as to make of it a kind of conglomeration of inter-dependent sewing machines.

Fifty years after the time of Watt the water turbine was first heard of in this country, and it came very quickly into prominence; but it was still another fifty years before any successful attempt was made to apply similar machines to the development of steam power. It is not to be supposed that no ineffectual efforts were made in this direction: the records of the Patent Office are full of unsuccessful experiments, but every one of these resulted in a machine so inefficient, and consequently such a fearful "steam-eater," that it had to be abandoned. The fact is, that it is not sufficient to produce a machine conforming to the general mechanical laws laid down for water turbines, in order to possess a satisfactory steam turbine. That such an engine must obey these laws (with certain modifications) is true; but it is also true that it must be designed in accordance with principles depending on the nature of the working fluid, and to which every steam engine must more or less conform.

In all heat engines, of which class steam engines form the most important section, the action is of one general type: the working fluid is heated, and rises in pressure, it then expands, doing work in the engine, and at the same time giving up a portion of its heat until it is dis-

charged, carrying off a certain amount of unused energy to the air or to the condenser. In steam engines, in particular, the heat derived from the furnace performs two operations, namely, converting the water into steam, and raising the steam to a high temperature and pressure. Now, after the steam has done its work it has fallen in temperature and pressure, but most of it is still steam, and is so discharged into the air or into a condenser; and exhaust into a condenser has this advantage, that, whereas the steam may in this case leave the cylinder at a temperature of 100° to 120° Fahr., and a pressure of say 2 or 3 inches of mercury, it can only enter the air at a pressure at least atmospheric, and a temperature above 212° Fahr.

Now, considering the case only of the condensing engine, which is much the more efficient—and practically all large steam turbines are now provided with condensers—we see that, of the heat given to the steam in the boiler, part is employed usefully in the cylinder, and part is taken on into the condenser and wasted in heating the condensing water. Of course, the lower the temperature and pressure at which steam enters the condenser the less heat will be wasted in this way, and the more complete will be the expansion in the cylinder. But in a reciprocating engine the amount of expansion that can take place in the cylinder is limited by the size of the cylinder, so that the benefit of a condenser can never be completely appreciated.

Suppose, however, that we have got a good vacuum in the condenser, so that discharge takes place from the cylinder at a pressure of ten inches of mercury and a temperature of 160° Fahr. Then every pound of steam going through the engine carries into the condenser a definite amount—1,131 units—of heat, and if the feed

water temperature were 70°, the boiler heat wasted in the condenser would be 600 units per pound. The amount of heat used in the cylinder depends on the total heat which the steam brought from the boiler. The greater the proportion of heat used to heat wasted, the higher the efficiency of the engine; and it is therefore important that each pound of steam should bring the greatest possible amount of heat from the boiler; in other words, that the boiler temperature (and consequently pressure) should be as high as possible; and for this reason the boiler pressure in a modern steam engine ranges from 150 to 250 pounds per square inch. To secure sufficient expansion, two, three, or four cylinders of increasing size are used in succession.

Consider, for a moment, to what head such a pressure would be equivalent in water turbine practice. The volume of a pound of boiler steam under a pressure of 200 pounds to the square inch, or 28,800 pounds to the square foot, is 2·3 cubic feet, so that the pressure is equivalent to that of a column of the steam 62,000 feet in height. Now if it is difficult, and we know that it is so, to design a turbine to run under a head of from two to three thousand feet, can we blame the inventors who found difficulty in producing a satisfactory turbine for a head of 12 miles?

As a matter of fact, it is found that steam from a boiler under a pressure of 200 pounds per square inch discharges into the atmosphere with a velocity of something over 3,000 feet per second, and if the steam be superheated to the extent of 100° Fahr. (a treatment which adds greatly to the economy of the engine) the speed of discharge is raised to about 3,500 feet per second. If we take the conditions under which turbines are most commonly run—with a boiler pressure, that is to say, of

150 to 200 pounds, considerable superheat, and a vacuum of about 27 inches of mercury—the free velocity of discharge from boiler to condenser will be over 4,000 feet per second. Even saturated steam at atmospheric pressure would discharge into a perfect vacuum at a speed of nearly 3,000 feet per second.

Perhaps the most suitable of all the turbines described in the former part of this work, for use under a head of great height, is the Pelton wheel; but a Pelton wheel, in order to develop efficiently the power of a jet moving at 4,000 feet per second, would have to rotate with a rim speed of 2,000 feet per second itself. Unfortunately, the outside limit of rim speeds with modern materials is considerably short of this figure, and for a steel wheel, having most of its weight in the rim, the limit is reached at about 700 feet per second, though no one would think of running this speed very close.

This problem, how to use a head so great that no single wheel can do justice to it, was the one confronting the would-be designers of steam turbines. A certain amount of guidance was afforded by Jonval, the inventor of the parallel flow turbine, who, when using a head of water too great for the speed which he wished to develop had in several cases erected two water turbines, one below the other, so that the second was run by the water discharged from the first, at a height of half the head. Jonval invented the system of compounding, on which every successful steam turbine, with one solitary and interesting exception, has been constructed.

CHAPTER II.

THE HISTORY OF THE STEAM TURBINE.

WE have already mentioned Hero's reaction wheel, the earliest known form of steam engine. Of course, this was a very inefficient machine, because, while the wheel turned slowly, the steam escaped with great velocity, carrying off all but a very small part of the energy which it brought from the boiler. Nevertheless, this machine was re-invented and patented by De Kempelen in 1784, under the style of "A Reaction Machine set in motion by Fire, Air, Water, or any other Fluid"; with the further explanation that it was primarily intended to be driven by "boiling water or rather the vapour proceeding therefrom."

Engineers were slow to drop the application of the reaction principle pure and simple; in fact there is a patent granted to one Francis Bresson, in 1852, for a method of driving a train by the reaction of a jet of steam projected out of the van, and many attempts were made to improve De Kempelen's wheel by increasing the number of arms, altering their shape, and so on. One really valuable suggestion was made by Burstall in 1838, to the effect that a set of arms curving in the opposite direction should be mounted on the same shaft, for the purpose of reversing the engine.

The first suggestion, however, that really went to curing

the radical defects of the reaction wheel, was that embodied in Hale's patent of 1836, which was, that steam issuing from a simple reaction wheel should be diverted to the use of a second wheel mounted on the same shaft. The mechanism by which Hale proposed to effect this diversion was unsatisfactory, as there was no adequate provision made for destroying the angular momentum of the steam about the shaft, between the times of its issuing from the first wheel and entering the second; however, the principle of the invention was sound enough.

From this time onward the possibilities of the steam turbine began to be realized, and among the numerous patents for water turbines which followed the success of Fourneyron's wheel, few can be found that do not claim the application of the same machine to steam power. For the most part these inventions are valueless, so far, at least, as steam is concerned, because they neglect the compounding essential to success; but there are a few which deserve mention.

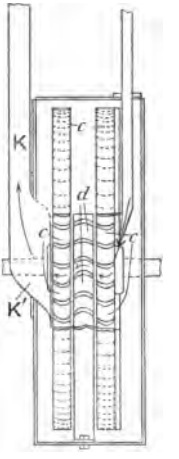

FIG. 36. HARTHAN'S TURBINE (1858).

The first in which any satisfactory attempt to compound the turbine is made, is the subject of a patent of Harthan in 1858. The machine consists of a pair of wheels with curved blades, through which parallel flow takes place; and between the two moving wheels are a set of blades exactly similar but reversed, so that the direction of the steam is changed between its discharge from the first wheel and its admission to the second. The turbine is therefore almost exactly like the modern De Laval, compounded by the addition of a second

wheel, but it lacks the peculiar nozzle to which the De Laval turbine owes its success.

A second ingenious inventor, after passing his steam through a parallel flow turbine wheel, conducts the exhaust by a looped channel into the same wheel again, and then again, until a number of impulses have been derived from it, and all its energy is communicated to the wheel. The obvious defect of this machine is that, as the steam expands further and further, its temperature continually drops, so that it cools down the blades through which it passes at its last admission to the wheel; and these, in turn, meeting the high pressure steam from the boiler, abstract heat from it, to the great detriment of the efficiency of the engine. In fact, this turbine defies the general principle that, where complete expansion is to take place, high pressure and low pressure steam must not come in contact with the same piece of metal. The different stages of the expansion ought to take place in different parts of the machine.

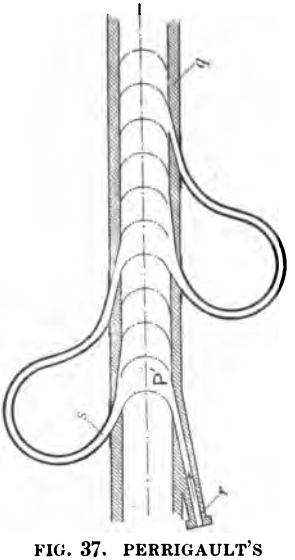

FIG. 37. PERRIGAULT'S TURBINE (1865).

A turbine free from this defect is described in the same specification (949 of 1865). The rotor of this machine contains a number of separate blade rows very similar to those in the earlier compound turbine. In this machine, however, the steam is conducted from row to row by channels, and the intention appears to be that the steam shall expand in these channels, and that the

pressure should drop, not in one step, as in the earlier machine, but in a number of stages corresponding to the number of blade rows. The author is not aware that this turbine was ever constructed; possibly the practical difficulties would have been found insurmountable in the early days of machine tools; the design of the steam passages, too, is not correct; but it might have been fairly successful. Harthan's turbine is practically identical with the smaller A.E.G. turbines now very popular in Germany, thanks to the improvement effected by the divergent nozzle, which is a feature of all modern machines. A combination of the two turbines of 1858 and 1865 has produced the American Curtis turbine, one of the most successful yet constructed.

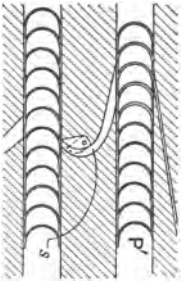

FIG. 38. PERRIGAULT (1865).

All these turbines are obviously impulse turbines, but we may now make use of a second method of classification of compound turbines, in addition to that on which we relied in the earlier part of this work—we may divide them into those in which the whole velocity due to the head of steam is developed in the nozzle at admission to the first wheel, as in Harthan's turbine; and those in which the pressure falls in a series of steps, and the velocity is developed and annihilated alternately. Turbines of the latter class are known as many stage turbines. Those of the former are commonly called single stage machines, but this description is not an accurate one, inasmuch as, although there is only a single pressure stage, the steam velocity is generally destroyed in a series of steps, and the turbine has therefore (except in a few cases) a number of velocity stages.

If we have to design a compound steam turbine of the single stage type (Fig. 35), to use a steam pressure of 200 pounds per square inch, we must recognize that the velocity developed at the nozzles will be of the order of 4,000 feet per second. Suppose, then, that we pass this steam through four rows of moving blades of the form adopted by Harthan, and through three intermediate rows of fixed blades of the same shape but reversed. Then the velocity parted with by the steam in passing through each moving row will be nearly twice that of the row itself. It will therefore be necessary to run each blade row at a speed of 500 feet per second, and the steam will then give up all its energy to the turbine. The small A.E.G. turbine is designed on these lines.

If, on the other hand, our object is a many stage turbine, we may still adopt the impulse type of machine, and the same rotor blades will still serve our purpose. It is required now that the steam should enter the first blade row with a velocity of 1,000 feet per second. This means a drop in pressure from 200 to just over 150 pounds per square inch in the nozzles. The same speed is required at admission to the second blade row, and a somewhat smaller loss of pressure (about 36 pounds) will be involved. The drop in pressure in the successive stages of passage through the turbine diminishes continually, so that the steam reaches atmospheric pressure only after some ten stages, each developing a velocity of 1,000 feet per second, and it does not attain a vacuum of 26 inches until the same velocity has been generated and destroyed another seven times. This is the action in the Zoelly turbine.

It must not be supposed, however, that the work done in the latter turbine is any greater than that done in the former, in spite of the increased number of blade rows, for, in the many-stage turbine, the work done in each row

is the same as that done in the last row of the single stage turbine, but, in the first row of the latter, seven times as much work is done, in the second row, five times, and in the third row, three times as much as in the last; the work done in each row being of course proportional to the change in energy of the steam as it passes through.

In the many-stage turbine, then, every row of blades is important, and each does its fair share of the work, whereas in the impulse turbine the first wheel bears the burden and heat of the steam, and the others could be abolished with nothing more than a loss of efficiency becoming less and less serious as the speed of the wheel is increased; a fact which will be strikingly brought to our notice in connection with the De Laval turbine.

We have barely outlined the principal conditions affecting the construction of steam turbines, but we have already entered more fully into the principles governing their operation than anyone had done before the Hon. C. A. Parsons produced the first steam turbine of practical and commercial merit, the first to be classed for efficiency and utility with the reciprocating engine, and the first at this day in popularity, among the creations of the large and increasing class of distinguished engineers who have followed in the path which Mr. Parsons found.

It seems proper, then, to give some account of the Parsons steam turbine, and of its rivals, before we digress any further into the rather tempting field of theoretical discussion.

CHAPTER III.

THE PARSONS STEAM TURBINE.

PARSONS'S turbine was invented in 1884, but its early form was very different from that of the huge machines which are turned out at Heaton nowadays, and as for its efficiency, it was a great day for the makers when they got the steam consumption down to 36 pounds per horse-power-hour.

This early form is very clearly described in the specification of the 1884 patent, which shows clearly the new and essential features of the turbine. And the really essential feature was this, that the engine was compounded of a number of simple turbines mounted on the same shaft. In fact, the rotor was at this time built up of a number of brass disks or wheels; the rim of each wheel was cut away, leaving a row of flat projecting blades oblique to the plane of the wheel, so that a blast of steam in the direction of the shaft would tend to turn the wheel, exactly as a windmill is turned by a blast of air acting on its sails.

But these blades were not subjected to a blast of steam parallel to the shaft; for outside each wheel was a brass ring, and the inner surface of each ring was cut away, leaving a row of inwardly projecting blades. The solid part of these rings when bolted together formed a cylinder which completely surrounded the turbine rotor,

fitting so closely outside the rotor blades as to allow just sufficient clearance for turning; while the rows of fixed blades, projecting inwardly from the cylinder, separated the moving rows one from another, and allowed the drum a bare clearance for rotation. These clearances were so small that steam, in passing from one end of the turbine cylinder to the other, had to pass through alternate rows of fixed and moving blades. Now the moving

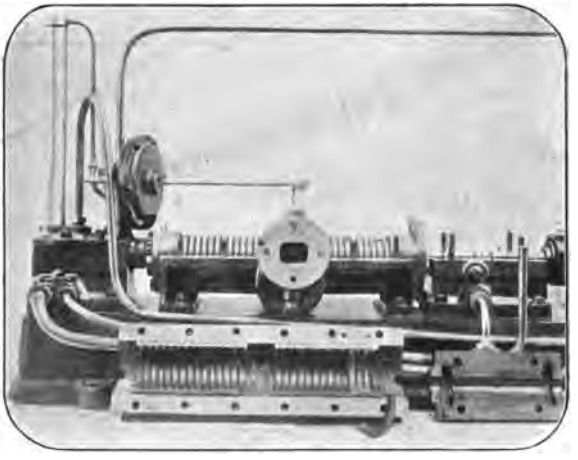

FIG. 39. AN EARLY PARSONS TURBINE OF 10 H.P.

blades and fixed blades were both oblique to the axis, as if they were parts of screw-worms, but of right and left-handed screws respectively, so that the blades of alternate rows were nearly at right angles, and the path of steam going through the turbine, while the rotor stood still, was a zig-zag with very sharp corners. Its general direction was then parallel to the shaft.

When the machine was running, the path of the steam between the rotor blades was affected by the motion of these blades, so that its general course through the

turbine changed; the direction being, on the whole, in a screw round the shaft, and the sharp corners being considerably flattened.

The first Parsons turbine was constructed in 1884 and is now very properly placed, as a machine of historical interest, in the South Kensington Museum. This turbine developed 20 H.P. at a speed of 18,000 revolutions per minute, and was coupled directly to a small dynamo. Steam entered the turbine case at the middle and flowed in either direction to the ends, whence it exhausted at atmospheric pressure. This design was followed in all the early machines, so that the turbines were symmetrical about their middle points, and the blading formed right and left-handed screws on the two halves of the rotor. Since the steam expanded in its passage through the cylinder, it was necessary to provide larger passages at the ends than at the middle of the machine. With this object the length of the blades was increased towards the ends of the turbine, and the diameter of the solid disks correspondingly diminished, so that the solid part of the rotor had a barrel shape, and the steam entered at the greatest diameter.

The first notable public appearance of the steam turbine was at the Royal Jubilee Exhibition at Newcastle-upon-Tyne in 1887, when the courts of the exhibition were entirely lit by turbine power. The smooth running and compactness of the machines used there received universal admiration, but unfortunately their daring novelty, combined with their more serious defect of a large steam consumption, caused engineers to regard them rather in the light of mechanical toys.

Efforts were now made to minimise the losses due to faulty design. It was found that, partly, no doubt, owing to the inevitable leakage of steam past the blades, which

took place pretty equally in large and in small machines, a much higher efficiency was attained by the larger than by the less powerful turbines; but a twenty H.P. turbine constructed on the old plan consisted practically of two ten-horse turbines abutting at the point of admission of the steam, an arrangement which secures, it is true, that the steam shall exert no end-wise pressure on the rotor, but which assigns to each turbine the efficiency which might otherwise be attained by one of half the size. It is clear, then, that by admitting steam at the end, instead of at the middle of the cylinder, economy can be materially improved, and size and weight reduced at the same time.

The disadvantage of a steam flow in one direction only through the cylinder is that it causes a pressure on the rotor, tending to displace it towards the exhaust end of the case and causing friction at the bearings; and it is very important that no such displacement should be permitted, lest the rows of fixed and moving blades should come into contact, with disastrous results. In 1887, however, Parsons patented a new form of turbine in which this difficulty was overcome, by the introduction of balancing pistons, and a considerable increase in economy was experienced with the new type of machine.

Although with the introduction of the condensing turbine, in which the ratio of expansion is much greater than in the early machine, an increase in the number of blade rows has been found necessary, and various other modifications in matters of detail have been adopted, yet the form of turbine shown in the patent specification of 1887 is substantially the same as that of the best machines in use at the present day.

For reasons unconnected with the science of turbine

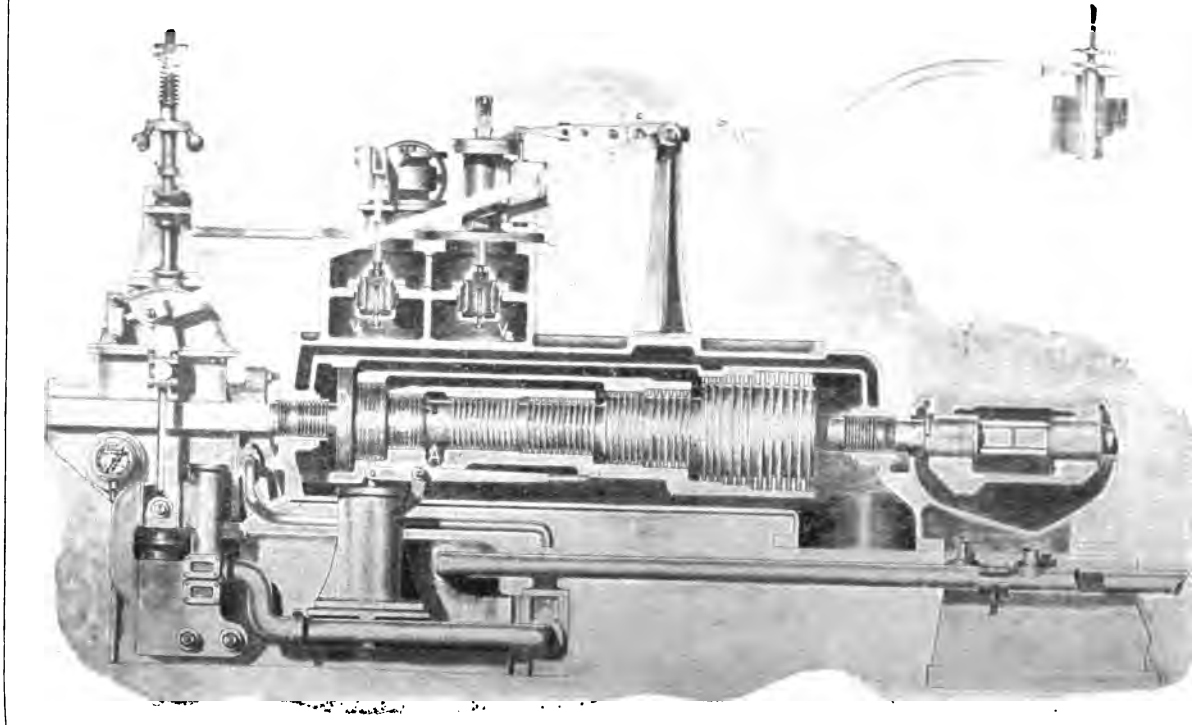

FIG. 10.—75 KW. PARSONS STEAM TURBINE WITH ELECTRIC GOVERNOR.

design, Mr. Parsons found it necessary to abandon for a short time the construction of parallel flow turbines, and to adopt the less satisfactory radial type, and the first condensing and the first marine turbine were both of this form. Subsequently the manufacture of the more efficient parallel flow turbines was again taken up.

In 1891, as at present, every steam engine which made any claim to efficiency was a condensing engine, exhausting, that is to say, not into the air, at a pressure above 14·7 pounds absolute, but into a vacuum more or less complete. In 1891 Mr. Parsons decided to construct a condensing steam turbine, being confident that a considerable improvement in economy would result. The first condensing steam turbine was built in 1892, and was, as mentioned above, of the radial type. In spite of this disadvantage, it showed, in a series of tests conducted by Professor Ewing, of Cambridge University, in 1894, the fairly economical consumption of 27 pounds of steam per kw.-hour at a pressure of 100 pounds per square inch, equivalent to about 16 pounds per indicated horse-power-hour in a reciprocating engine, a result about equivalent to that which might be expected of a compound engine of the same size.

These tests took the steam turbine once and for all out of the category of toys, and the return to the parallel flow type of turbine, with condensation, resulted in a further increase of efficiency, which put the steam turbine almost, if not quite, on a level, in the matter of steam consumption, with the triple expansion engine. Still further improvements have been made in recent years, and, while it has not been found possible, up to the present, to equal the efficiency of the triple expansion engine in the smaller turbines, a marked improvement is apparent in the larger machines, and with every in-

crease in the size of the set, the advantage of the steam turbine over the reciprocating engine becomes more obvious.

In a test of a 3,500 kw. turbo-alternator at the Carville power station in February, 1905, in the course of which the machine was run under a 40% overload for the space of an hour, the consumption was 15·4 pounds of steam (at pressure 199 pounds and 150° superheat) per kw.-hour when running at a load of 4,142 kw., 15·87 pounds at the full overload, and only 15·94 pounds per kw.-hour at the approximate half load of 1,896 kw. This test shows the maximum efficiency at 20% overload: The steam consumption then is 15·4 pounds per kw.-hour, amounting, if we assume the very high dynamo efficiency of 95%, to a consumption of 10·6 pounds per B.H.P.-hour, a result better than any that has been obtained from a reciprocating engine.

A 4,000 kw. Parsons turbine, built by Messrs. Brown, Boveri and Co., of Baden, has achieved a steam consumption of only 14·74 pounds per kw.-hour, and it seems reasonable to suppose that with the increasing size of the units the economy will be still further increased.

But the advantage of the turbine over the reciprocating engine does not stop here. Having regard to the far better results achieved by the large turbines than by the smaller ones, it is fair to assume, and it is vigorously contended by the designers of the Parsons turbine, that the steam consumption of a 10,000 kw. machine could be reduced as low as 13 pounds per kw.-hour. In addition to this advantage, the small space occupied by the turbine gives to its user a great advantage in the matter of capital outlay on buildings and the like, while the cost even of the smaller turbines is little greater than that of

a good reciprocating engine of the same size. It has been found that the large steam turbine has a great advantage over the reciprocating engine in the matter of first cost, and Mr. Parsons declared before the Committee of the House of Lords on the "Administrative County of London and District Electric Power Bill," his willingness to undertake the construction of a 10,000 kw. steam turbine, at five times the cost of a 1,000 kw. machine, that is to say, at little more than half the cost of a first class reciprocating engine of the same power.

CHAPTER IV.

THE PARSONS TURBINE APPLIED TO ELECTRIC GENERATION.

SUPPOSE that we approach a steam turbine of 1,000 kw. output, that is to say, of about 1,400 I.H.P., running in one of the big electrical power stations where these turbines are becoming so common and so popular. We see a large barrel of blue steel, of which one end is almost hidden in the regulating machinery, while the other merges into a massive iron casting, forming at once the end of the cylinder and the bearing of the turbine shaft. From this bearing we see the shaft emerge to enter the dynamo. The cylinder is supported at both ends. The base at the end near the dynamo has the form of a large ring, together with a rectangular pedestal, which carries the bearing bushes. At the other end the support is a long pedestal carrying, not only the cylinder end and bearings, but also a certain amount of other gear. On top of the cylinder stands a steel clad steam chest, containing certain valves. We can recognize easily the steam pipe entering this chest and the enormous exhaust pipe disappearing through the bed-plate at the base of the cylinder near the dynamo.

With the regulation of the turbine we will not concern ourselves for the moment, but fall to upon the bolts of the steam chest and the regulating and other surround-

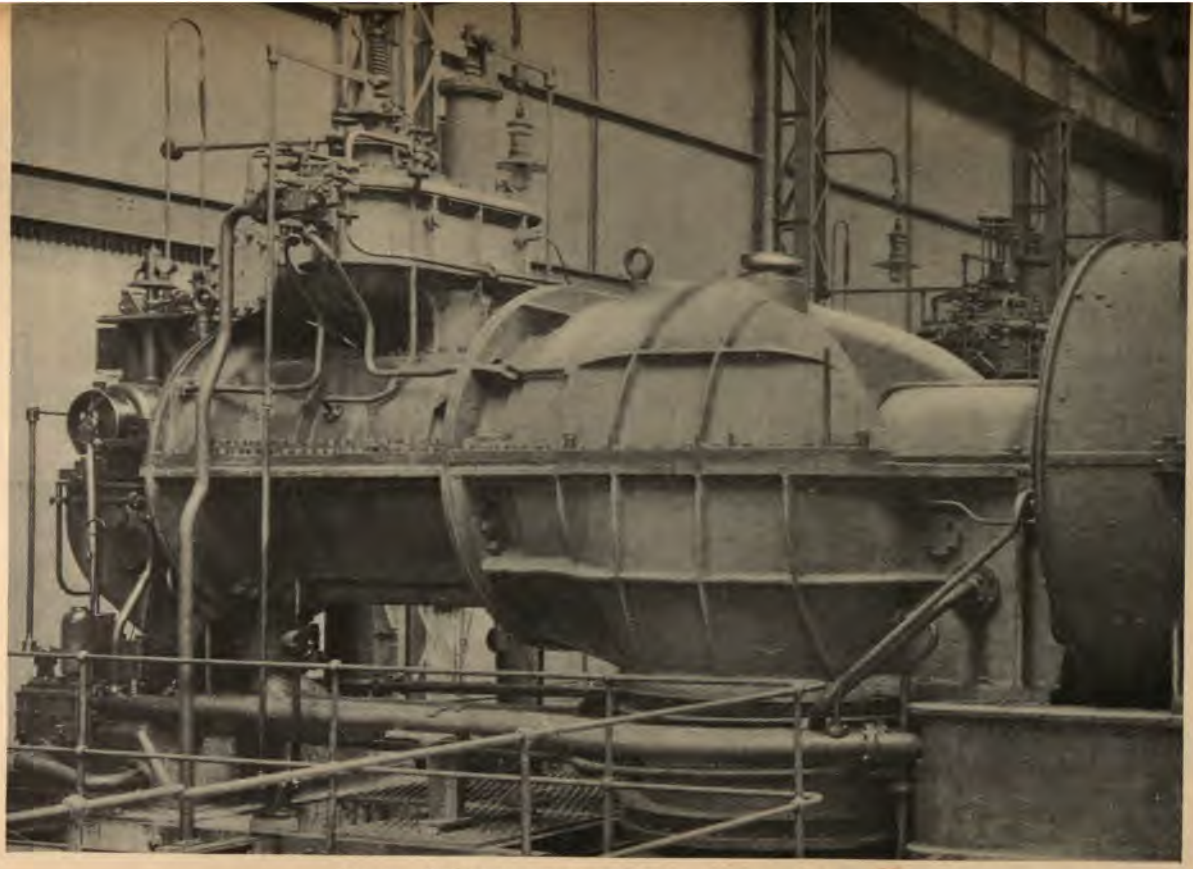

FIG. 41. 3,500 KW. TURBO-GENERATOR AT CARVILLE.

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ing machinery, and we can very quickly have the steel cylinder stripped of all encumbrances. At the end of the turbine, remote from the dynamo, is a long pedestal, and over the outer end of the pedestal is a small cover, forming with the pedestal itself a kind of box. This is one of Mr. Parsons's patented devices, and has for its object the prevention of longitudinal motion of the shaft.

The shaft under this cover is grooved in rings, and semicircular grooves are turned both in the cover and in the hollow face of the pedestal, forming together a set of circular rings, which engage with those on the shaft and form a thrust block similar to that in a marine engine room. But the beauty of the device lies in this, that, unlike the top of a thrust block, the top of this keeper is susceptible of delicate adjustment by means of screws, so that wear on the keeper rings may be taken up, and the position of the rotor very nicely defined.

From the keeper the shaft emerges into view. Here it carries a stout worm, designed to engage with a worm wheel which we have already removed, and which should make one revolution for every thirty or so made by the turbine shaft. Of this wheel and its appurtenances we shall speak more anon. The oil pump is driven from the shaft of this wheel by a connecting rod visible in the photograph.

Next the shaft disappears under a second and larger cast iron cover concealing the gun-metal bushes which carry one half of the weight of the rotor. These bushes are lined with soft white metal, such as Babitt's metal, and are supplied with oil under high pressure, so that the shaft is almost oil borne. The bearing carries the shaft right up to the wall of the cylinder, which it enters without again becoming visible, but at the junction of the cylinder and bearing covers we could detect, if the turbine

were running, a faint leakage of steam as from the spout of a kettle beginning to boil.

The cylinder itself is about 15 feet long, and appears to be of uniform diameter, but we shall find that the blue steel cleadings are only attached by small screws to give a finish to the appearance of the engine, and as it is the construction that we wish to examine, we shall very quickly demolish them.

Stripped of its trappings, the turbine cylinder looks like nothing so much as a large Egyptian sarcophagus. From the low pressure end, where the cylinder is wide and rests on the large ring which vents into the exhaust pipe, or, in the best installations, direct into the condenser, it tapers down by a series of steps and then suddenly flares out again to the original diameter, as if making provision for the feet of a mummy; but the inhabitant is something much more lively and vigorous than the inhabitant of a sarcophagus. At the narrowest part of the case a small platform is formed to carry the steam chest, and the port in its face enables us to catch a glimpse of the rotor. All we can see, however, is a bright steel barrel, rather larger than the shaft visible outside, and to get a more complete idea of its construction we must remove the cover of the turbine case.

The cylinder is made in two halves, divided horizontally. Both parts are flanged and planed up to a true fit, so as to form a steam-tight joint. The upper half is fitted with ring bolts, by which it may be slung from a crane and so removed. When we have raised it we have reached the heart of the engine and our exploration will be well rewarded.

The inside of the cylinder is almost entirely filled by the spindle of the rotor, and the intervening space is filled with row after row of little blades attached alternately to

the spindle and to the cylinder case. The cylinder cover, too, bristles with a little forest of brass.

The body of the rotor is formed by a steel casting or forging. Its shape may be seen in the figure, from which it will be gathered that it consists of three or four long drums, and of an equal number of short drums or disks, increasing in size from the chamber A (Fig. 43) to which steam is admitted, to the chamber E_2, which communicates with the exhaust. The long drums increase in

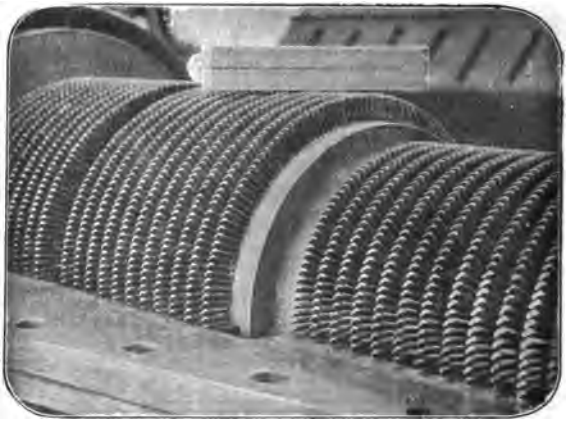


FIG. 42. ROTOR OF MODERN STEAM TURBINE.

size from the chamber A to a chamber which is at the end of the turbine near to the dynamo and in communication with the exhaust. Each of the disks is of slightly greater diameter than the corresponding drum, but of smaller diameter than the section of the case surrounding that drum.

A certain amount of space filled with blades is left between the case and the drums, particularly the large low pressure drum, but the disks on the other hand fit the case very closely, and, instead of being garnished

with blades, carry circular projecting ridges which engage with grooves in the case to form a practically steam-tight rotating joint. Between consecutive disks, however, there are slight recesses forming chambers, and the case is slightly recessed at A, to form a high pressure steam chest.

At each end, also, there is considerable clearance between the rotor and the ends of the cylinder, so that chambers of considerable size are formed (E_1, E_2, Fig. 48), each of which is connected to the condenser, and in each of which there is, therefore, an almost perfect vacuum. Lastly, there are small chambers (B_1, C_1, D_1) formed at the shoulders of the rotor between consecutive drums, so that the steam emerging from the blades on one drum is brought, relatively speaking, to rest before it enters the guide blades which direct it on to the first row of blades on the next drum. Each of these chambers is connected by a small pipe or channel to the corresponding chamber between the disks. These channels are formed in the cylinders of the smaller turbines, but external pipes are used with the larger ones.

It appears, then, that when the throttle is shut there is a vacuum throughout the cylinder, but when the throttle is opened and steam at high pressure is admitted to the cavity A, the situation is changed, for the steam naturally seeks a passage to the chambers in which there is a vacuum. Now the disks at the one end of the rotor fit the cylinder closely, so that there is no passage for the steam in that direction, except in very small quantities, and it must find its way between the long drums and the cylinder.

This is where the blades are set. Each drum is garnished with a number of rows of blades, and all the blades on each drum are of the same size and shape; but they vary

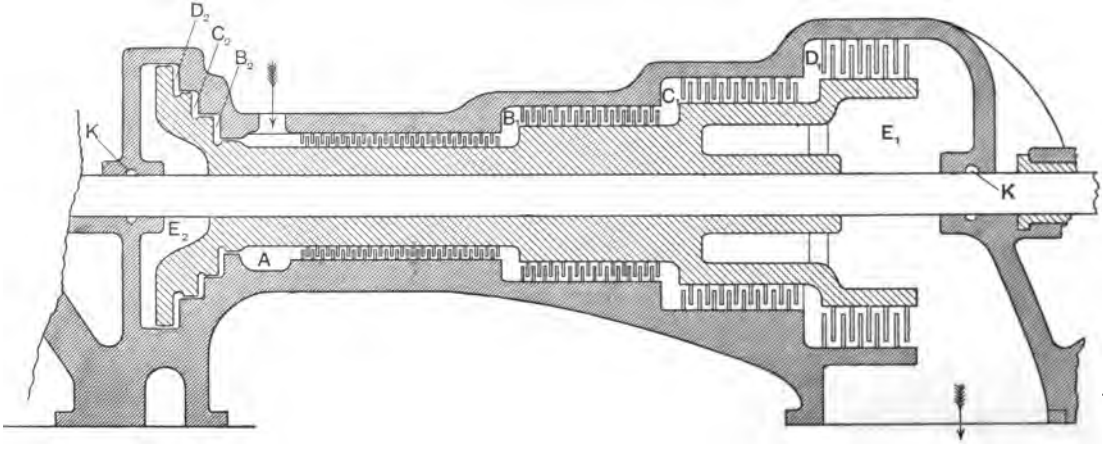


FIG. 43. SECTIONAL DIAGRAM OF 1,000 KW. TURBO-GENERATOR (NOT TO SCALE).

a little in the method of setting from one end of the drum to the other. The scheme of blading is something like that shown in the figure. The shaded blades are those that project inwardly from the case and are attached thereto, the blades shown in blank project outwardly from the rotor and run in the direction indicated by the arrows. It is clear that the volume of the steam increases greatly between the two ends of any drum, and it follows that its velocity must increase

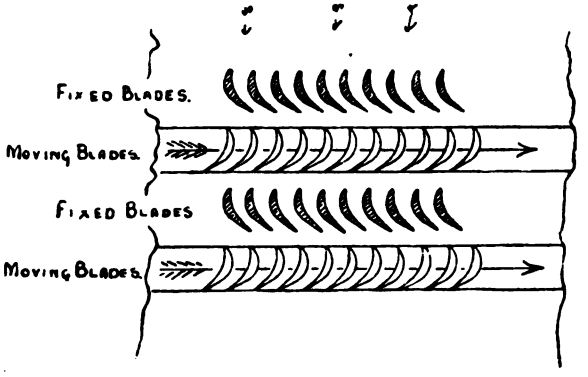


FIG. 44. BLADING OF PARSONS'S TURBINE.

correspondingly, in order that it may pass the channels. The blades are so arranged as to get the full benefit of the different velocities at admission to the various rows, according to the principles of blade design laid down in Chapters IV and VI of Part I. At the same time the width of the steam channels is slightly increased near the low pressure end.

The similarity of blading of the Parsons steam turbine and of the Jonval water turbine is apparent, and it will be clear to the reader that in consequence of the restriction of each blade passage (whether fixed or moving) at the

discharge end, this is a true reaction turbine, so that the pressure falls not only in each passage through the guide rings, but also in each passage through the moving blade rows, a feature which forms the fundamental distinction between the Parsons turbine and those of Zoelly and Rateau. Each of the rows in which the pressure falls is known in the technics of turbine design as a "pressure stage," and it will perhaps help the reader to picture correctly the operation of the various turbines which we shall describe, if we premise that the De Laval turbine has only 1 pressure stage, the Curtis 3 or 4, the Zoelly as many pressure stages as moving blade rows, generally about 10, the Rateau on the same grounds 15 or 20, and the Parsons and Schultz turbines, twice as many pressure stages as moving blade rows, that is to say, from 40 to 400 in all.

The ratios of expansion in the various pressure stages are not the same. We have already pointed out that the steam velocities increase towards the low pressure ends of each drum; and it is clear that, since each of the rotor drums is larger than the preceding one, the blade speed, and consequently the steam velocity, increases from drum to drum. The increase of steam velocity is therefore continuous throughout the turbine, and since the velocity developed in any expansion depends on the ratio of expansion, it follows that the ratio of expansion in each pressure stage is continually on the increase. While, however, we should do wrong to assume the same ratio of expansion in each blade row, we can make a very accurate assumption that the total expansion on each drum is the same. If, then, there are four drums (as will be the case on a turbine of some size) and if superheated steam be admitted to the cylinder at a pressure of 180 pounds per square inch abs., the condenser pressure

being $1\frac{1}{2}$ pound abs., then the absolute pressures in the three intermediate chambers will be 52, 16, and 5 pounds respectively.

Now let us—premising that these figures differ considerably from those adopted in the construction of modern turbines, and that the resulting design will therefore be rather different from that of the large machines, of which it would obviously be unwise to give details—

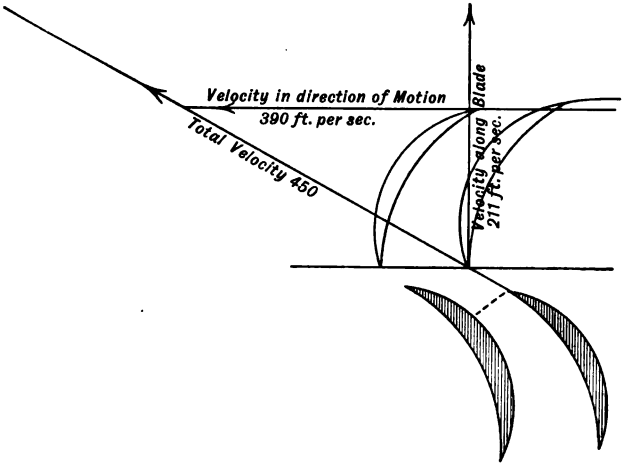


FIG. 45. STEAM VELOCITIES.

assume a total of 45 moving blade rows, of which 20 shall be set on the high pressure drum, and 12, 8, and 5 on the other three drums. There are then 40 pressure stages on the first drum, and the mean expansion in each stage is therefore 3·12, an expansion capable of developing a steam velocity of nearly 400 feet per second. Now suppose that one end of the blades is parallel to the axis, and that the other is inclined at 60° thereto; if the speed of the steam is 450 feet per second at discharge from the fixed blades, this is equivalent to a speed of 390 feet per

second in the direction of the blade's motion, together with a speed of 225 feet per second along the blade. The expansion in the moving blade row will raise this last speed again to 455 feet per second relative to the rotor, so that steam enters the next fixed row with a velocity along the blades of 228 feet per second.

If there is to be no impact the blade speed of the first drum should be 390 feet per second. As a matter of fact, impact is not very disastrous, owing to the elasticity of steam, and a blade speed of 250 feet per second will serve our purpose excellently. If, then, the diameter of the rotor be 1 foot, the speed will be 4,800 R.P.M.

We have now to find the length of the blades on the small drum. If the machine is to be capable of a maximum load of 1,000 kw. it must be capable of passing 30,000 pounds of steam per hour through the blade row under consideration, and this at a speed of 450 feet per second. The aggregate width (at the narrowest part) will be found to be almost exactly 1 foot. The pressure of the slightly superheated steam at this point is about 110 pounds, so that the volume of 1 pound is nearly 4·5 cubic feet; the quantity of steam to be passed per second is therefore $37\frac{1}{2}$ cubic feet. This gives for the height of the blades $37\frac{1}{2}/450$ foot, or 1 inch.

Now if we turn our attention to the last drum, we find that the mean expansion in each pressure stage is $13\frac{1}{4}\%$. The velocity due to this expansion is slightly over 800 feet per second. The steam velocities on the last drum are therefore just over twice those on the first, and the blade speeds must of course be increased in the same proportion. The diameter of the low pressure drum ought, therefore, to be 2·06 times that of the high pressure drum, or 2 feet $\frac{3}{4}$ inch, and the aggregate width of the steam passage round this drum will be 2·06 times as great as

that of the high pressure passages. Now the volume of the steam is increased in the ratio 32:1, and the velocity in the ratio 2·06: 1. It appears, then, that the ratio of increase in the length of the blades should be $32 \div (2{\cdot}06^2)$ or about 7·5:1, so the low pressure blades must be $7\frac{1}{2}$ inches long.

The reader can apply the same method to calculate out the elements of design of the other drums. A similar process will enable him to work out the elements of all the other turbines now on the market, and each is capable of simple theoretical treatment, provided the assumptions made are reconcilable with the laws of thermodynamics, a condition precedent which too many turbine designers have been rash enough to neglect.

The blades (both fixed and moving) are mounted on the rotor or cylinder in circular channels cut in the steel, according to a patented process. Into these channels the feet of the blades are inserted, alternately with small distance pieces, until the circle is nearly completed, when a good deal of mechanical ingenuity is called into play in inserting the last blades and wedging the whole firm. Special tools are used for this purpose, and, when the whole ring is fitted, the blader goes over the circle once more to make sure that all blades are evenly spaced and properly erect. Any faulty blade can be easily extracted and replaced.

For the better securing of the erection and fixity of the blades they are further stayed, in all the larger machines, by connections at their outer ends. In the small turbines only the long low pressure blades are so connected.

The fixed blades are exactly the same in size, shape, and setting, as those in the corresponding moving row, and, except that they direct the steam in the opposite

sense, their action on it, and that of the steam on them, is exactly the same as in the moving rows. Quite apart from this consideration, however, it is obvious that the torque exerted by the steam on the rotor and cylinder must be the same, so that if the cylinder were free to turn it would revolve in the opposite sense to the rotor, and at a speed depending on the resistances. It has been suggested that an application of this fact might be made to electrical generators, for the purpose of reducing the centrifugal forces, since it is evident that one rotor might rotate under these circumstances at half the present speed, and an application to marine propulsion has also been discussed. Though the principle is used to a certain extent in the Seger turbine, the various engineers who have endeavoured to adapt the Parsons and other powerful engines for its use have now abandoned the attempt.

One more part must be noticed before the cylinder cover is replaced. The shaft emerges from the rotor at both ends into a chamber in which there is an almost complete vacuum, and from this chamber it passes into the open air. These low pressure spaces are directly connected with the condenser, and the importance of keeping the condenser free from air is well known to every engineer. Vast quantities of steam enter the condenser from the cylinder, but these are there condensed so that the pump has only to deal with a comparatively very small quantity of water; if air should leak in, since this cannot be condensed, it has to be pumped out at great inconvenience, and a high vacuum becomes impossible, and since turbines are designed to use advantageously a much higher vacuum than is commonly found in connection with reciprocating engines, very careful provision against leakage is necessary in their design. It is therefore of the utmost importance that no air should enter

the turbine cylinder at the ends. To guard as far as possible against leakage a series of rotating pistons is formed on the shaft at the point where it penetrates the cylinder end, and these run like the disks on the rotor in brass sleeve rings fitted to the cylinder itself.

These rings and sleeves form a rotating joint through which, in any case, there could be very little leakage, but as it is of the utmost importance that there should be

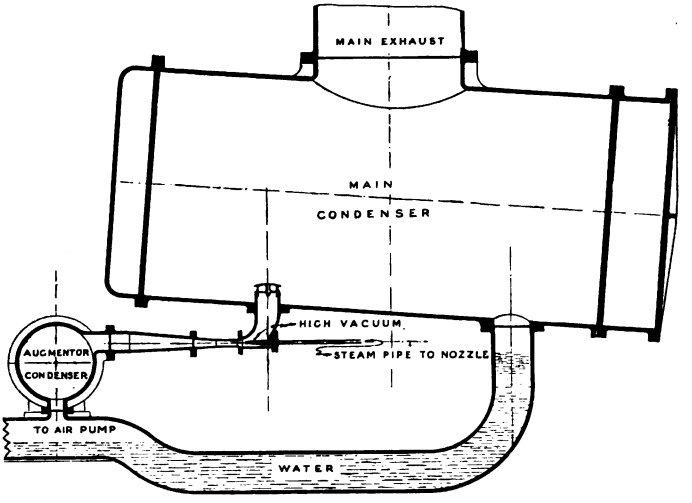


FIG. 46. PARSONS'S VACUUM AUGMENTOR.

none whatever, steam from the main steam pipe is led through a narrow tube into the middle ring (K, Fig. 44) so that it reaches the packing rings at a pressure a little above the atmosphere. Some of this steam leaks into the condenser and is so returned into the boiler; a little may be seen escaping into the outer air and effectually preventing the leakage of air into the turbine cylinder.

We have already pointed out that it is possible to use a much higher vacuum in the turbine than in the recipro-

cating engine, because while the steam is at rest in the reciprocating engine it is flowing at a high velocity in the turbine cylinder, and a large specific volume does not therefore imply a cylinder of corresponding size. To secure this high vacuum is the function of the vacuum augmentor (Fig. 46). This is an ejector steam jet by which the steam remaining after a part has been condensed at a very low pressure in the main condenser, is drawn off and condensed in a second condenser where the pressure is higher. The water from both condensers mingles and is returned to the boiler. By this augmentor a vacuum of 28 inches of mercury can be secured in the main condenser, while that in the air pump is only 25 ins.

Admission to the turbine cylinder takes place through a port in the top of the cylinder cover in the large machines (in others by a steam pipe), and a steam chest containing the admission valves is secured by bolts above the aperture, or seated, in a small turbine, upon the cover. There are two double beat valves in the chest (Fig. 39): the first, V_1, is a runaway valve, permanently open unless the controlling apparatus refuses to work. The second, a similar valve, V_2, is operated by a piston working in a chamber above it, and the motion of the piston is in turn controlled by the slide valve in the steam chest alongside. The position of this slide valve depends on three different adjustments. In the first place, the floating lever from which the valve is suspended is supported at one, end, D, by the governor, which may be a mechanical one, or electrical, as shown in the figure. This governor is itself susceptible of adjustment to varying speeds. The fulcrum, E, of the floating lever, is on a second link fixed at one end, but rising and falling at the other with the motion of a cam carried by the worm wheel previously referred to, and rising and falling about twice in each second.

The result of this arrangement is that the slide valve oscillates continually, but its centre of oscillation is fixed by the governor. The steam is therefore admitted to the turbine when running at full speed in a series of periodic blasts the duration of which the governor determines; but while starting, or when much overloaded, the blast is continuous, and the highest efficiency is consequently often obtained with considerable overload.

In starting the turbine we first raise the runaway valve and then open the throttle very slightly, so as to expel the air from the cylinder without spoiling the vacuum in the condenser. Then the stop cocks leading the steam to the keeper rings are opened to guard against any return of the air.

Now comes the critical moment. One man has his hand on the throttle; a couple more begin to raise the great sluice gate that shuts off the exhaust. One turn of the wheel puts the cylinder into communication with the condenser, and the rotor is now lying in a vacuum. Slowly the throttle is opened. Now the sluice is raised with a will to give a free passage to the expanded steam, and the gauge on the high pressure steam chamber rises suddenly from 13 pounds below, to 180 pounds above, the atmospheric pressure. The gauges on the intermediate chambers rise more slowly as the rotor gathers speed.

For the turbine began to run at the moment when the throttle was opened. One would hardly know it, so quiet is the motion, but just at the first moment it is possible to see the shaft and the rotor of the dynamo beginning to turn. Before a minute is past they are running so fast and so smoothly that they seem to be at rest. One can trace the increase of speed, if there are pressure gauges on the chambers, as there are when a trial is being made, for, as the speed increases, and the impact

of the steam on the blades diminishes, the pressure in the first chamber rises slowly to about 38 pounds, while pressure in the next chamber rises up to a pound or two above the atmosphere. In the chamber D_1 the vacuum remains unaltered until full speed is almost attained, when it diminishes gradually by about 10 inches of mercury.

Now it is very clear that the steam acting on the blades and contained in the chambers must exert a considerable endwise pressure on the rotor which would tend in time to wear out the thrust block, while causing some frictional resistance to motion. But it will be remembered that the chambers at the opposite ends of the cylinder are in communication, so that the pressures above referred to are exactly balanced by the pressures on the disks at the other end of the rotor, and consequently there is absolutely no endwise pressure exerted. In fact, the bearings of the turbine carry the weight of the rotor only, and are subject to no other stresses whatever, a state of perfection which it is impossible to attain in any other form of prime mover.

The weight of the rotor itself is, as a matter of fact, carried to a large extent on a layer of high pressure oil supplied to the bearing, so that the rotor is really floating altogether, but this bearing is entirely outside the turbine cylinder, and the steam itself never comes into contact with any sliding parts, any packing or any lubricating oil, an advantage to the boilers which can hardly be overrated.

CHAPTER V.

THE MARINE STEAM TURBINE.

MR. PARSONS, in producing the first commercially successful steam turbine, would have done his generation no mean service had the usefulness of the engine been confined to the stationary generation of power; but to the same inventor belongs the credit of having been the first to apply the turbine to a purpose for which its peculiar features render it even more conspicuously suitable than for that of electrical generations.

In 1894 the Marine Steam Turbine Co., Ltd., was formed, and under its auspices the *Turbinia* was built at Wallsend-on-Tyne. The *Turbinia* was rather a trial to her owners at first. Low speed turbines had not then been developed, so that the shaft (she commenced her career with a single propeller) made 2,000 revolutions per minute, and it was not practicable to run a propeller of any size at that speed. The two-bladed propeller of 30 inches diameter which was first fitted got no sufficient grip of the water, and others were little more satisfactory. The best result was obtained with three propellers on the shaft. Their slip was 37·5 per cent., and the speed attained was 19¾ knots.

The original shaft was now replaced by three separate ones, each driven by a turbine. We are familiar with the compound turbine as constituted of three or more

FIG. 47. "TURBINIA" STEAMING AT 34 KNOTS.

separate drums in one cylinder, the steam passing from drum to drum. Now the *Turbinia* was driven by a turbine set consisting of three drums in different cylinders, the high pressure turbine driving the starboard shaft, the intermediate the shaft to port, and the low pressure turbine the central shaft. The change in driving power due to this re-arrangement was enormous, and, after a little further experiment with propellers, the then unsurpassed speed of 34 knots was attained over a run from Spithead to Southampton Water, a distance of about twelve miles.

The length of the *Turbinia* is 100 feet, beam 9 feet, draught 5 feet 6 inches, and with her full crew on board, in sea-going trim, she displaced 44½ tons. The actual propulsive H.P. at a given speed is very difficult to determine from direct measurement. It might be done if there were any vessel capable of towing her at the speed in question; failing that, the horsepower must be worked out from tank experiments with models. In this way it has been estimated that the propulsive H.P. at 31 knots was 905, and at 32 knots 980. The consumption of feed water at the lower speed was measured as 27,000 pounds per hour; at the higher speed it was estimated to be 28,200, or 28·8 pounds per propulsive H.P.-hour. Similar calculations in the case of high speed vessels driven by reciprocating engines have led to the conclusion that the proportion of propulsive power to the power developed in the engine is between 55 and 60 per cent.; that is to say, the efficiency of a high speed screw is from 0·55 to 0·6. The most efficient of such reciprocating high speed marine engines have shown a steam consumption of about 18 pounds per indicated H.P.-hour, or say 30 pounds per propulsive H.P.-hour, a steam consumption more extravagant than that of the *Turbinia*.

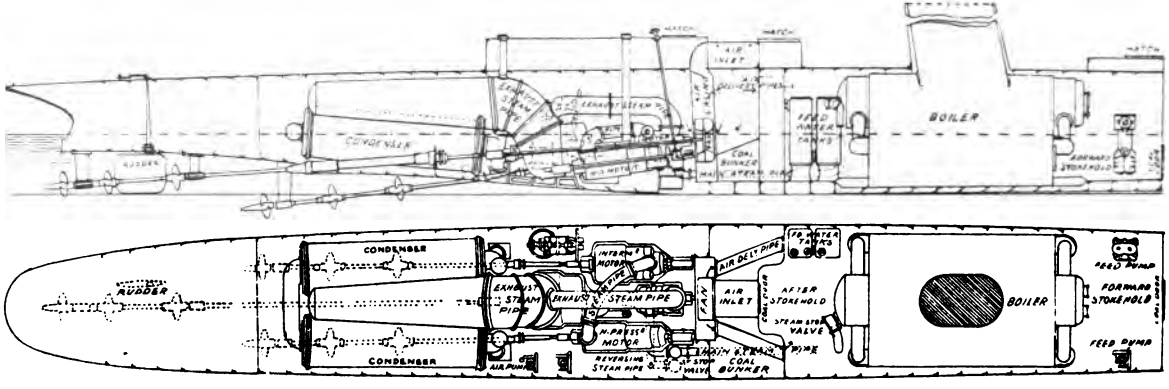


FIG. 48. MACHINERY AND PROPELLERS OF S.Y. "TURBINIA."

It has always been one of the chief difficulties of high speed work at sea to design an efficient screw. Large slow-moving screws are generally used for trading vessels, where economy is the only criterion of merit, but the propellers of small and fast boats, such as torpedo boats, are necessarily run at higher speeds.

So long as the propeller is large enough to get a good hold of the water, no diminution of efficiency appears to

FIG. 49. CAVITATION, 4,000 R.P.M.

result from the adoption of a small diameter, and correspondingly high speed; on the contrary, the excellent results attained by the propellers of the *Carmania* would appear to indicate that a gain in efficiency is the natural result of such a modification; and this gain may perhaps be attributed in part to the decrease in surface friction on the propeller. When, however, we adopt a very high speed of running, a new trouble makes itself felt. It is inevitable that the water should derive a certain rotation from the propeller with which it is in contact, and when

the speed of this rotation is considerable, "centrifugal force" comes into play, and forms a kind of submarine whirlpool surrounding the propeller and tail shaft. This phenomenon is known as cavitation, and results in a serious diminution of the driving power of the propeller, combined with an increase in slip. The speed at which the shaft may be run depends on the pressure of the water surrounding the cavity (inside which there is a vacuum relieved only by a negligible steam pressure), and this in turn depends on the submersion of the screw. The shafts of the *Turbinia* were inclined to the horizontal for the purpose, among others, of securing adequate submersion.

In the turbines finally adopted on the *Turbinia*, steam passed through each cylinder from the fore to the after end, whence it was led to the fore end of the next cylinder in the series. Provision was made for the expansion of the steam in the course of its passage through each cylinder by increasing the height of the blades towards the stern, so that the section of the passage was increased while the rotor remained a uniform drum.

The general effect of the steam on the rotor and shaft was therefore a turning couple, together with a direct thrust aft. Had the turbine been devoted to the purpose of driving a dynamo, it would have been necessary to balance this thrust by disks on the fore end of the shaft in the manner described in the last chapter; but the circumstances are here completely changed, the water is exerting a forward pressure on the propeller, and so on the shaft, and it will obviously be desirable, if possible, to balance this pressure against that of the steam. This was, in fact, done, so far as careful calculation and experiment could do it.

The situation was therefore this. Each shaft was carried in a number of gun-metal bushes, the bushes being themselves mounted in a series of concentric tubes separated by thin films of oil under pressure, so that a very slight vibration of the bushes might take place without being felt in the vessel. These bearings carried the weight of the shaft, propeller and rotor; but, in addition to the weight, the shaft was subject to a forward thrust exerted by the water, and to the opposing thrust of the steam. The rotor was so designed that these two thrusts practically balanced one another when running at full speed, and, at that speed, the shaft ran practically free in the bearings, unlike the shaft of a vessel fitted with reciprocating engines, which grinds continually against the thrust block, by means of which it transmits the propeller's pressure to the hull. The actual force driving the hull in a turbine vessel is not a thrust derived from the shaft directly, but the forward pressure of the steam against the fore end of the turbine cylinder. So that we have really got the steam pressing forward on the hull and backward on the water by means of the shaft, which acts as a buffer between steam and sea.

It was not possible, of course, to trust entirely to the balance of steam and water pressure to maintain the equilibrium of the shaft, particularly in an engine in which the consequences of an endwise displacement of the rotor would be so serious as in those of the *Turbinia*; each shaft was therefore fitted with a thrust block which, at starting or stopping the turbines, as well as while running at slow speeds, had to carry a considerable load.

The ends of the turbine cylinders were fitted with brass rings projecting into grooves in the rotor and steam sealed, according to the system in use ashore. The central or low pressure shaft carried, between the turbine and

the fan for forcing the draught, a small reversing turbine used for going astern, since to reverse the propelling turbines was impossible.

The speed of 2,200 revolutions per minute, for which the turbines were designed, was considerably lower than that generally in use at the time in stationary steam turbines, and it was necessary, in order to secure adequate blade speed, to adopt a correspondingly larger diameter of rotor. To maintain a moderate section of steam passage it was necessary to use short blades and many of them, so that the various parts of a marine steam turbine have a very different appearance from those of an electrical turbo-generator. Even so the blade speeds of a marine steam turbine are not usually so high as those of the stationary machine, and the stages of expansion are therefore still further subdivided by the use of a large number of blade rows. Instead of permitting complete expansion from boiler to condenser in a single turbine cylinder two or three such cylinders are used in series, each containing a separate drum, and driving a separate shaft, but the whole forming only a single turbine set.

In the *Turbinia* three drums were used, of which the high pressure one drove the starboard shaft, the intermediate that to port, and the low pressure the central one. The slip of the propellers on the two side shafts was found to be about 26 per cent. and that of the central one 16 per cent. This difference is no doubt due in part to the fact that the central propeller was acting on water following in the wake of the vessel; it may be doubted whether it is fair to infer that the low pressure turbine did less than its fair share of the work.

In modern practice, at any rate, it is usual to connect the two low pressure drums in parallel, and to drive the central propeller by the high pressure drum. In some

cases, the central propeller is the largest of the three and is run at the lowest speed, so that the greatest duty is put upon the high pressure drum, while high steam velocities are utilized in the other two.

The *Turbinia* finally established the utility of the steam turbine for the propulsion of high speed vessels, and in the year following her official tests two orders were placed with the Parsons Marine Steam Turbine Co. for sets of high speed marine turbines. The one was fitted in the *Cobra*, built by Armstrong, Mitchell and Co., and afterwards purchased by the Admiralty, the other equipped the torpedo boat destroyer *Viper*, built by the Turbine Co. to the Admiralty's own order.

These two ships, *Viper* and *Cobra*, were very nearly alike, both in engines and in general design, and were of nearly the same dimensions as the 30 knot destroyers previously constructed, viz., length 210 feet, beam 21 feet, and displacement 370 tons.

The tragic fate of the *Cobra* is not yet forgotten; she had passed through a number of trials with credit, and attained the speed of 34 knots without showing any signs of strain, and was being taken at an easy cruising speed from the Tyne to the Thames, when she broke completely in halves during the night, and was lost with all her crew.

There can be no doubt that this misfortune was due in the main to the excessive lightness of the ship's build, and happily the lesson taught by her sad example has not been altogether lost. But it is exceedingly unfortunate for the progress of marine turbines and of the British navy, that the winds and waves should have chosen for scapegoat the second destroyer to be fitted with the new engine, giving occasion to amateur mathematicians and newspaper experts to shake their heads and talk about

the gyroscopic effect of steam turbines as responsible for the occurrence. We shall hope to show in a later chapter that this criticism is little more reasonable than that rhetorically put by the average seafarer, "What could they expect when they gave her a name like that?"

The engines of the *Viper* and *Cobra* were, as we have stated, of very similar pattern, and the action was substantially the same as in the *Turbinia*. The destroyers, however, had four shafts, driven by two high pressure turbines on the outer shafts discharging into two low pressure turbines on the inner ones. On each shaft were two propellers, the after of the two having a slightly greater pitch than the forward one.

The system of tandem propellers has now gone out of vogue. The real reason for its adoption was the high speed of the shafts. This made it necessary to use propellers of moderate pitch and diameter, and a number of these must be employed to get a sufficient grip of the water. There were then two alternatives, either to use a large number of shafts and corresponding number of turbines, which adds to cost and diminishes efficiency —for small turbines are always comparatively wasteful —or else to set a number of propellers on every shaft. The whole problem has now become somewhat academic, as it has been found practicable to run the turbine rotors at much slower speeds than were thought possible in the early days of their application to marine purposes, but it is now held that, even on the fastest running shafts, it is better to fit a single propeller of comparatively large diameter than a number of smaller ones of the same pitch arranged on the tandem system. This view would seem to be confirmed by recent experiments on the *Turbinia*.

This problem of propeller design is an extremely in-

teresting one. The simple theory is that each blade of the propeller is a part of a screw surface, and that as the shaft turns, this screw traverses the water, exactly as a joiner's screw traverses a plank. The water, however, does not offer to the propeller the same firm substance that the wood offers to the screw; the same force which urges the vessel forward throws the water back. If the propeller is mounted, as it should be, almost clear of the disturbance in the water effected by the passage of the hull, then it cuts into practically still water as it goes forward, and as it cuts into it, the water is thrown back. The action is that of a Jonval turbine reversed, so that the blades might well approximate to the form of those in the Jonval turbine, or more nearly to the form of a bird's wing on the down stroke, slightly concave on the after surface and convex forward. In fact, however, the blades are usually made of a true screw form. The propeller presses on the water astern and sucks in that ahead, creating a backward moving stream. The propulsive force is proportional to the speed of this stream, to the speed of the propeller through it, and to the section of the stream, which is the area of the propeller circle. Thus the propeller is continually driving through what is practically a head tide of its own making.

Suppose that the speed of the vessel is 18 knots, and that the water is streaming past the propeller with a velocity of 3 knots towards the stern. The average speed of the water on which the propeller is acting is 3 knots, and the shaft must, therefore, run as if the ship were making 21 knots instead of 18, the slip of the propeller is then 3 knots or 14%, and 14% of the work done by the engines is wasted from this cause, besides that wasted by friction of the water on the propeller surface.

The case against tandem propellers is briefly this. The second propeller on the shaft, instead of cutting into smooth water, enters water which has already been in contact with the leading one, and which is, therefore, moving with a speed of 3 knots in the opposite direction to that of the motion of the propeller. *Caeteris paribus*, the water will pass the blades with a velocity of 6 knots, and the mean slip of the second propeller will be 6 knots or 25%, the shaft running as if the ship were making 24 knots. In like manner, if there were a third propeller on the shaft, it may be taken that its mean slip would be 9 knots or 33⅓%. Of course all these propellers being on the same shaft, their speed of rotation must be the same, and the different degrees of slip must be allowed for by giving them different pitches, as was in fact done in the *Viper* and *Cobra*.

In the above discussion we have, for simplicity, treated the action of the screw on the water as if it were a direct thrust. As a matter of fact, it is nothing of the sort, though the practical effect of the action is not thereby altered. The actual motion of the water in leaving the propeller is a screw motion, as may be very well seen from the stern of a liner under full steam, particularly if she be a twin screw vessel. This motion is even more fatal to the efficiency of a second propeller on the same shaft than is the direct flow considered in the above paragraph.

We have referred to the propeller as a kind of reversed Jonval turbine. This scarcely represents the state of affairs accurately, as every true turbine has fixed as well as moving blades; the screw propeller is really a reversed reaction wheel of the kind described on page 14, and is subject to the same limitations of efficiency as the reaction wheel. The way to render the propeller a true

turbine would be to add fixed blades, forming a propeller of very large pitch, set in the reverse sense to the moving ones. In this way the screw motion of the water might be used for propulsion, and it is possible that where tandem propellers are used, some real benefit might be derived from setting such fixed blades on the bearing brackets between consecutive screws. Attempts to adopt some such device have not, however, met with any success.

The contract speed of the *Viper* was 31 knots, and she was bound to do half speed astern. At her actual trials she attained a speed of 36·581 knots, the revolutions per minute being 1,180, and she successfully achieved the guaranteed 15½ knots astern. The reversing was accomplished by turbines carried on the low pressure shafts and permanently coupled to the condenser. These turbines, like the propulsive ones, were steam sealed, after the fashion of those described in the last chapter, so that, when the ship was going ahead, the reversing turbines ran in an almost complete vacuum, and caused very little waste of energy. They were very small, since the power spent in reversing at half speed is only about one-eighth part of that required to drive the vessel at full speed ahead.

A conspicuous feature of the *Viper's* engines, as compared with those of the *Turbinia*, was the reduced speed of rotation. This was obtained partly by increasing the diameter of the rotors, and partly by increasing the number of rows of blades on each. The reversing turbines were of smaller diameter than the propulsive ones, and their efficiency was very low as compared with that of the propulsive machines, which used 2·38 pounds of coal per I.H.P.-hour at full speed ahead, a very large consumption compared with that of modern turbine vessels.

The British navy then possessed the fastest vessel afloat, an advantage which does not appear to have been properly appreciated at the Admiralty, as the next class of destroyers ordered consisted of 25-knot boats fitted with reciprocating engines.

The action of the Admiralty is the less to be lamented, since it compelled Mr. Parsons to turn his attention to

FIG. 50. H.M.S. "AMETHYST."

the adaptation of steam turbines to the needs of the merchant service, where their merits met with a more ready recognition.

* * * * *

The *Viper* was wrecked on the Casquets in a fog during the naval manœuvres of 1901, and for some time the British navy included no turbine propelled vessels. In 1902 the *Velox* (T.B.D.) of 400 tons was purchased; and

in 1904 the *Amethyst*, built by Armstrong, Whitworth and Co. for the British Government, was launched, and was fitted with turbines by the Parsons Marine Steam Turbine Company.

This vessel is, not only in design, but also in boiler capacity, an exact counterpart of the other cruisers of the *Topaze* class, and so gave the first opportunity of a precise comparison of the merits of steam turbines and of reciprocating engines. Each of these vessels is of length 360 feet, beam 40 feet, and about 3,000 tons displacement. They were designed for a speed of 21·75 knots.

In the actual trials, which took place in 1904, the *Amethyst* attained a speed of 23·6 knots as against 22·1 developed by the *Topaze*, while the coal consumption of the turbine vessel was 38½% less than that of the sister ships. The turbines of the *Amethyst* were in fact more economical than the reciprocating engines of the other vessels at all speeds exceeding 15 knots, while the smaller weight and bulk of the turbines allowed her a greater bunker capacity, so that her radius of action in time of war would be about 50% greater than that of her rivals.

To appreciate the full significance of these results, it must be borne in mind that the *Amethyst* was the largest vessel at that time fitted with steam turbines, and that the design of her machinery was, therefore, to a great extent experimental, whereas the other ships of the class were propelled by reciprocating engines of a perfection only to be attained by long experience of similar work.

At the time when the tests of the *Amethyst* took place, the success of the marine steam turbine was already assured, but these results announced it to the public and to the engineering profession in a far more

striking fashion than ever before, and formed a fitting climax to twenty years of steady, but not always very obvious, progress. The Admiralty appreciated the improvement to the full, and resolved very properly to adopt

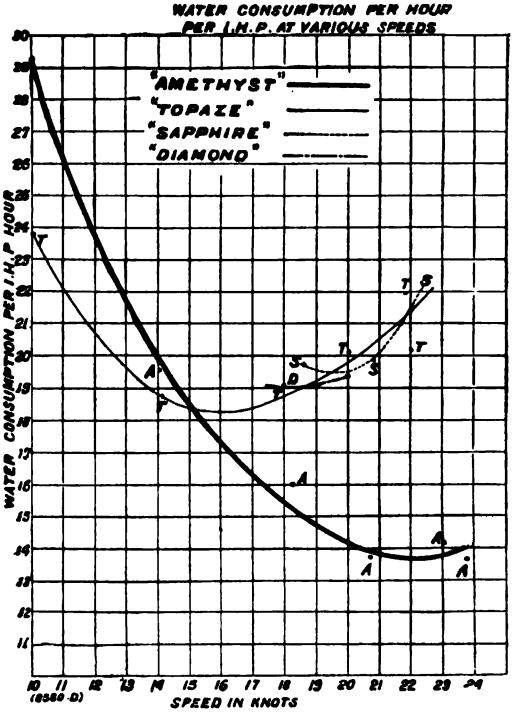


FIG. 51. TURBINES AND RECIPROCATING ENGINES. THE FIRST COMPARISON. (BY PERMISSION OF "ENGINEERING.")

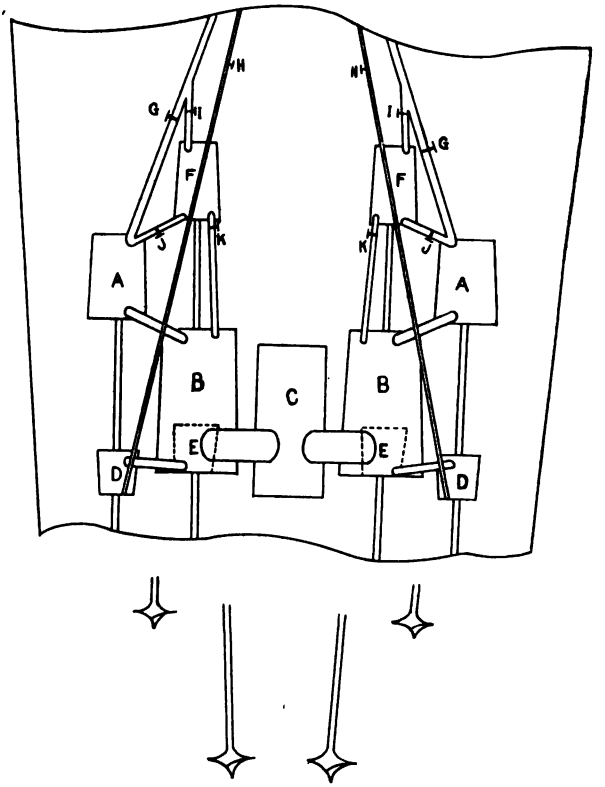
turbines throughout the navy. Every ship laid down during the year 1905 is to be fitted with Parsons turbines, including the *Dreadnought*, the first line of battleship to be so propelled, and the revolution in marine engineering long prophesied by those interested in turbines is accomplished at last.

The *Amethyst* was the first vessel in which an arrangement now common in turbine propelled warships was adopted.

In these vessels, although a high speed is necessary in case of war, the usual cruising speed is, for the sake of economy, very much lower. Now the only method of regulation possible for a Parson's marine turbine is that of throttling, which is an exceedingly wasteful method for two reasons, firstly because it takes away from the effective head of steam at admission, and secondly because the quantity of steam being reduced, with no corresponding decrease in the section of the wheel channels, the full steam velocities are not developed in these channels in the most desirable way.

If, however, the steam could be partially expanded while doing useful work before admission to the high pressure turbine, both these objections would lose their weight. This expansion was effected on the *Amethyst* by means of a high pressure and an intermediate cruising turbine, carried on the two outer shafts, which also bore the reversing and the low pressure turbines. When full speed was required, the cruising turbines ran in vacuo, but for low speeds steam was passed through the cruising set and then through the main set. The increased resistance in its path reduced the flow of steam without throttling, and a very large expansion was secured, as is done in a reciprocating engine when the cut off is shortened. The turbine escaped the great losses which arise from the variations of temperature in the cylinders when the reciprocating engine is so regulated.

In the battleship *Dreadnought*, which exemplifies the latest developments in marine turbine work, there are to be two sets of main turbines, the high pressure drums driving the outer shafts, and the low pressure drums the



A. Main H.P. turbines.
B. Main l.p. turbines.
C. Condenser.
D. Astern H.P. turbines.
E. Astern l.p. turbines.
F. Cruiser H.P. turbines.
G. Main throttles.
H. Astern throttles.
I. Cruising and emergency throttles.
J. Cruising intermediate steam valves.
K. Emergency intermediate steam valves.

FIG. 52. DIAGRAM OF PROPOSED TURBINE ARRANGEMENT OF H.M.S. "DREADNOUGHT."

inner. Two high pressure cruising turbines are also carried on the inner shafts, and from these the steam will pass to the ordinary high pressure turbines for low speed work. It has been suggested that these cruising turbines may be used in parallel with the main high pressure drums for the development of very large power on emergency. The whole set would not then permit of expansion nearly so complete as in the normal case, and this is the more to be regretted that the boiler pressure is to be very high (250 pounds). The arrangement is not likely, therefore, to prove entirely satisfactory so far as economy is concerned, but this must, of course, be sacrificed in times of emergency.

Another feature of the *Dreadnought's* machinery which deserves mention is the fact that she is to carry high and low pressure astern turbines on the same shafts with the main high and low pressure drums. She will, therefore, have ten turbine cylinders in all, forming four complete turbine sets.

It is estimated that this vessel will be two knots faster than any battleship previously launched, an advantage which the battle of the Japan Sea has enabled naval architects to appreciate at its full value, and which goes a long way to support the suggestion that the naval supremacy of the future lies with a turbine propelled fleet.

CHAPTER VI.

THE TURBINE IN THE MERCHANT SERVICE.

IT seemed in 1901 as if, in spite of the efforts made by the believers in the steam turbine to secure its adoption for marine purposes, science and enterprise had been overcome by mere idle prejudice, and the struggle were all to begin again. The *Cobra* was lost under the tragic circumstances previously referred to, and the Admiralty seemed to look on the turbine with a far from favouring eye. The Parsons Marine Steam Turbine Company were at that time the only firm willing to construct turbines for marine propulsion, and the works of that company had been for some time almost idle.

At this juncture a firm which has throughout been the best of friends to the steam turbine, decided to give it a trial in a branch of marine enterprise different from that to which its use had been hitherto confined. Messrs. Wm. Denny and Bros. were among the promoters of Turbine Steamers Limited of Glasgow, and built for that company the triple screw passenger steamer, *King Edward*, of 562 tons. This vessel was launched in the year 1901, and was engined by the Parsons Marine Steam Turbine Company. Triple expansion was abandoned in this vessel, and the turbines driving the two outer shafts were coupled in parallel; an arrangement which has been more or less faithfully maintained in the subsequent passenger steamers.

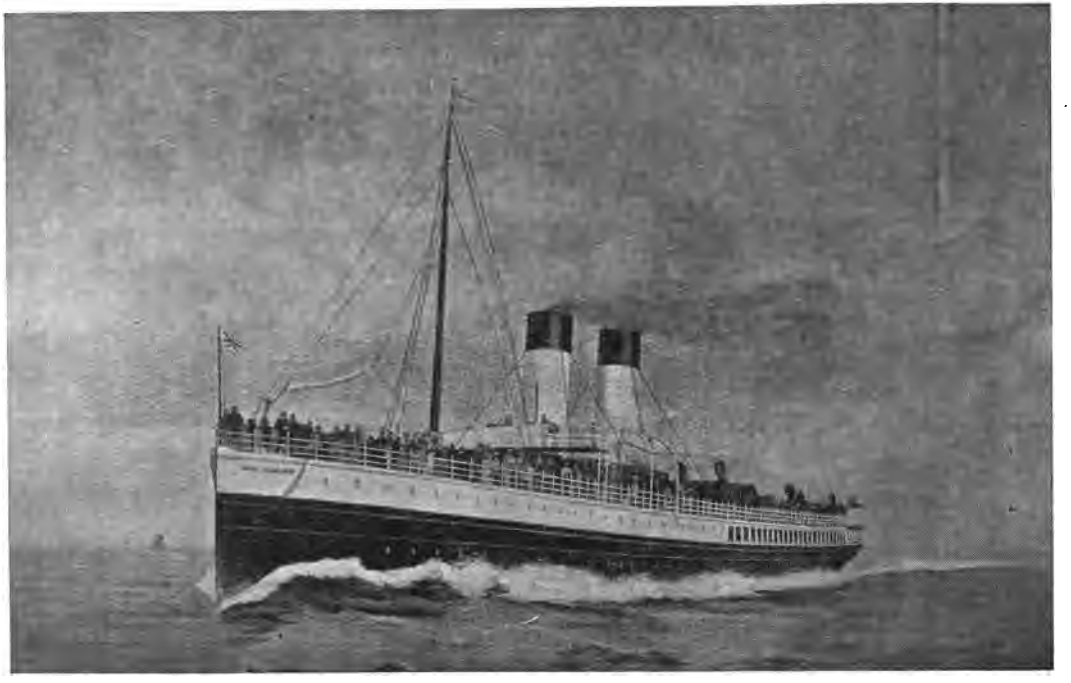


FIG. 53. THE TURBINE STEAMER "KING EDWARD."

In the *King Edward*, therefore, the installation was precisely symmetrical. The high pressure turbine drove the central shaft, carrying, according to figures given in a paper by Mr. Parsons, a single propeller 57 inches in diameter, while the two outer shafts carried each a pair of smaller propellers of 40 inches diameter, and a small reversing turbine (D, Fig. 54) running in the same cylinder with the low pressure drum, and discharging into the same exhaust, E.

We have already pointed out, in connection with the

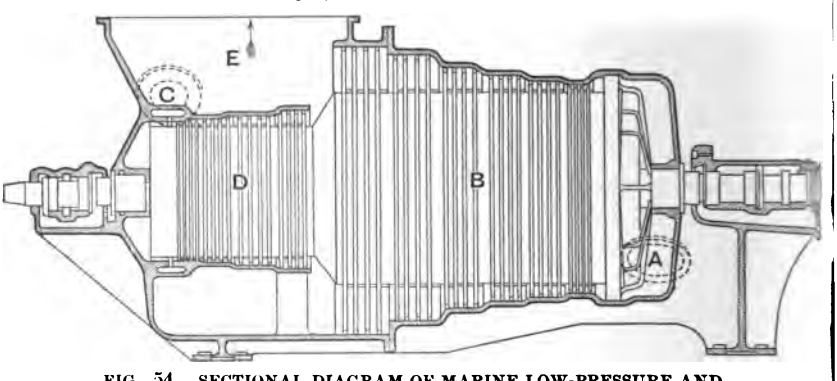


FIG. 54. SECTIONAL DIAGRAM OF MARINE LOW-PRESSURE AND ASTERN TURBINE.

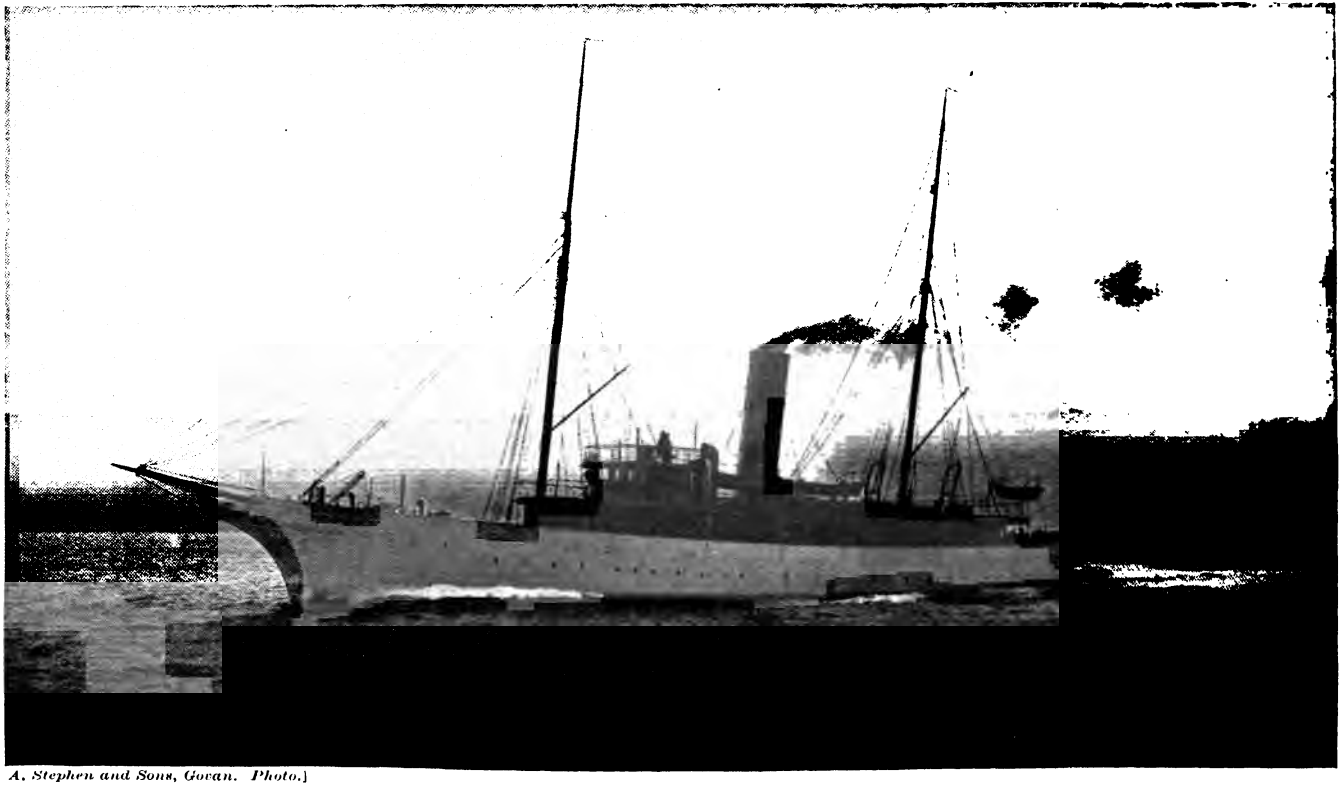
design of steam turbines for stationary work, that it is desirable to have faster moving blades at the low pressure than at the high pressure end of the cylinder, in order that the expanded steam may pass through more rapidly without loss of efficiency. This condition is secured in most marine steam turbines by the use of larger drums in the low pressure than in the high pressure cylinders. The method adopted on the *King Edward* was to run the outer shafts faster than the middle one, but the modern modifications of design, which have made it possible to run the machines at the comparatively low speed of 180

R.P.M. adopted on the *Carmania*, have done away with the necessity for this curious arrangement.

The *King Edward* achieved a speed of 20½ knots on her trial, the speed of the middle shaft being then 505, and of the outer shafts 755 R.P.M., speeds notably smaller than those obtained with the turbines previously constructed.

Up to the time when the *King Edward* entered upon her trial, no opportunity had occurred of comparing the efficiency of the marine steam turbine with that of the reciprocating engine, for turbines had only been fitted to vessels running at a speed unattainable by those propelled by reciprocating engines. The steam turbine was peculiarly well fitted for the propulsion of light, fast boats, as these could be driven by small screws rotating at a high speed; but in adapting the machines to the requirements of heavier and slower vessels, it was essential to design rotors which should run at a comparatively low speed with a high efficiency, and grave doubts were entertained as to the possibility of this modification. It appeared, however, from the tests of the *King Edward* that the turbines developed an even higher power than could be obtained from the best reciprocating engines with the same steam consumption.

The next turbine steamer constructed after the *King Edward* was a somewhat larger vessel of very much the same type, and built by the same firm, the *Queen Alexandra*. The success of these two vessels, the economy of their machinery, and the great increase in comfort resulting from the smooth running of the turbines, led the railway companies to take up the new prime mover, and from that time a very rapid advance was made both in the number and in the size of vessels fitted with turbine machinery. Several turbine yachts were launched soon



A. Stephen and Sons, Govan. Photo.]

FIG. 55. S.Y. "EMERALD." THE FIRST TURBINE VESSEL TO CROSS THE ATLANTIC.

after the *Queen Alexandra*, and one of these, the *Emerald*, was the first turbine vessel to cross the Atlantic.

The boldest step of all was, however, taken by the Allan line, in laying down the turbine vessels, *Victorian* and *Virginian*, of 11,200 and 11,400 tons, a tonnage nearly five times as great as that of any turbine steamer then building. The turbines in these two ships are arranged on the usual system, that is to say, with the high pressure drum driving the middle shaft. The outer shafts are driven by low pressure drums connected in parallel, and carry in addition reversing turbines for the purposes of manœuvring and of going astern. The weight of each low pressure turbine is about 70 tons, and the speed of the shafts 350 R.P.M. The vessels were designed for speeds of 18 knots, but following the honourable traditions of turbine steamers succeeded in attaining 19½.

The last and largest of turbine propelled steamships will be observed by engineers and ship builders with greater interest than any previously constructed, and this not only on account of her gigantic dimensions.

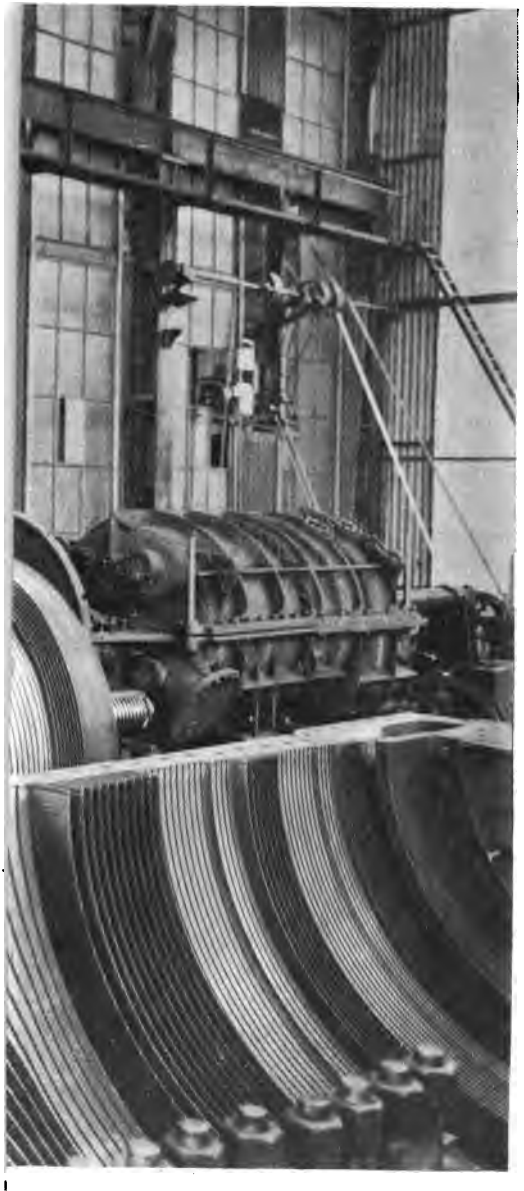
In 1903 Messrs. John Brown and Co., of Clydebank, laid down the *Caronia*, gross tonnage 19,500, for the Cunard line, and early in 1904 they commenced the building of the twin ship *Carmania*, identical, in every respect except the engines, with the *Caronia*. The latter ship was fitted with twin screws driven by quadruple expansion reciprocating engines at 84 revolutions per minute. The *Carmania*, on the other hand, is propelled by three screws equal in all respects, and driven by a high pressure and two low pressure turbines arranged on the usual system. These turbines made 180 revolutions per minute, a much greater number than has ever previously been adopted on a vessel of the same size, but, on the other hand, a

number scarcely more than half as great as the least for which earlier steam turbines had been designed. Having regard to the high speed of the shafts, the diameter of the propellers is kept very small as compared with that of the *Caronia's* screws. The blades are made very wide to secure an adequate grip of the water, and a very pretty trefoil propeller form results.

The *Carmania* is 672 feet 6 inches long over all, and displaces, when loaded, 30,918 tons. The hull of the *Caronia* is identical, except that the supports of her reciprocating engines are necessarily heavier than those carrying the turbines of the sister ship. The boilers also are of the same shape, but differ inasmuch as those of the *Carmania* are designed for a steam pressure of 195 pounds to the square inch, and those of the *Caronia* for the pressure of 210 pounds, a point in favour of the *Carmania* that can best be appreciated by a sea-going engineer. A comparison of these two vessels will therefore afford the very best test that could be desired of the relative merits of the perfected reciprocating engine and of the steam turbine. This comparison has been eagerly anticipated by all those interested in marine engineering.

The guaranteed speed of each vessel was 19 knots. The *Caronia* on her trial, with a clean bottom, attained the speed of 19·5 knots with an indicated horse-power of 23,000. The *Carmania*, with a very foul bottom, attained 20·19 knots, and by comparison with the tests of the *Caronia* the builders of both vessels have estimated that, with a clean bottom, the *Carmania* would be capable of 20·6 knots, representing a gain in horse-power and efficiency of about 15 % to the credit of the steam turbine.

As we have already pointed out, the principal difficulty in the way of the adaptation of steam turbines to the requirements of large ships, such as the *Carmania*, has



N," PARTIALLY BLADED.

[*At page* 172.

always been that of producing a turbine which shall be efficient at the very low speed required for driving screws large enough to propel these enormous hulls. The speeds of running of the largest stationary steam turbines, turbines, that is to say, of somewhat lower power than the *Carmania's* high pressure drum, are generally about 1,300 revolutions per minute. For marine purposes it is desired to run at a speed of not more than 180 R.P.M., and for this purpose it is necessary first of all to diminish the speed of each blade row, and secondly, by the adoption of a large diameter for the drum, to secure a moderate rotary speed in spite of a high peripheral velocity.

In order to secure a low speed for the blades without sacrifice of efficiency, it is necessary to arrange that the speed developed by the steam in passing from row to row shall be very much less than in the high speed turbine; it follows that the drop in pressure from row to row must be diminished, and the number of blade rows correspondingly increased. The large number of rows makes it advisable to separate the drums in different cylinders, so as to form a compound or triple expansion turbine; and, to satisfy the second condition, drums of a very large diameter are used.

The marine steam turbine is consequently a much larger and heavier engine than a stationary turbine of the same power, and, although the drums are hollow and constructed as lightly as possible, the weight of each of the low pressure turbines of the *Carmania* is 340 tons, as against the corresponding weight of 78 tons for the *Victorian*. According to figures communicated by the builders to engineering, Dec. 1st, 1905, the diameter of each low pressure drum is 11 feet. The large circumference enables a large flow of steam to pass through a somewhat narrow space between rotor and cylinder, so

that the blades are small, and a large number of blades in each row is therefore necessary. When we consider also the large number of rows in the whole turbine set, it becomes abundantly clear that the work of blading a liner's turbines is no trifle. There are in fact 1,115,000 blades in the *Carmania's* turbines, and every one of these is separately fitted by hand.

The outer ends of the blades, throughout the machinery, are secured by a brass band, arranged with a telescopic extension to permit of the necessary expansion and contraction.

The reversing turbines are carried on the outer shafts immediately abaft the low pressure turbines, and within the same casing, so that ahead and astern turbines exhaust into the same space (Fig. 54). The rotors are so formed that the steam pressure exactly balances the thrust or pull on the shaft at full speed ahead or astern. For manœuvring, steam is admitted to the low pressure turbines from the boiler, through a reducing valve, while the high pressure drum rotates idly in a vacuum.

At certain intervals in the casings of all the turbines, recessed grooves are bored, forming small chambers which may be connected with a pressure gauge. When the turbines are running, the pressure should fall steadily from chamber to chamber, and any accident within the cylinder will be immediately revealed to the engineer in charge by these gauges. In the extremely improbable event of any of the blades coming to grief, travelling cranes, fitted in the engine room for this purpose, are brought into service, and the cylinder cover, and rotor if necessary, are removed from the injured machine, while the others continue their duty.

Any faulty blade can be very quickly replaced, and, if necessary, a whole row, or several rows of blades, can be

entirely removed without spoiling the action of the engine. A case is on record in which a Parsons turbine ran for several days, and ran satisfactorily, when a number of blade rows had been completely stripped by the unexplained presence of a one-inch bolt in the turbine cylinder.

Owing to the high speed, the absence of complicated stresses near to the cranks, and the small diameter of the screws, it has been found possible to use lighter shafting in the turbine driven *Carmania* than in the sister vessel; the hollow turbine rotors are also lighter than reciprocating machinery, so that there is a very considerable gain in the weight of the moving parts, and consequently in the rapidity with which the propellers can be reversed, stopped, or accelerated. The *Carmania* has been successfully manœuvred in the Clyde, without the help of the rudder.

There can be little doubt but that the turbines of the *Carmania* are the most carefully planned and successful yet constructed, but even they must yield in interest to the remarkable sets which are to propel the Cunard greyhounds now building.

The vessel now in course of construction by Swan, Hunter, and Wigham Richardson, Ltd. is 760 feet long between perpendiculars, 88 feet in beam, and will register about 30,000 tons gross with a displacement of over 40,000 tons. She is to be capable of mounting several quick-firing guns, and her guaranteed speed of 25 knots will make her a notable addition to the British reserve fleet.

The engines will consist of four Parsons turbines driving four separate shafts for propulsion, and two astern turbines mounted on the inner shafts. These engines will be arranged on the twin system, the inner shafts

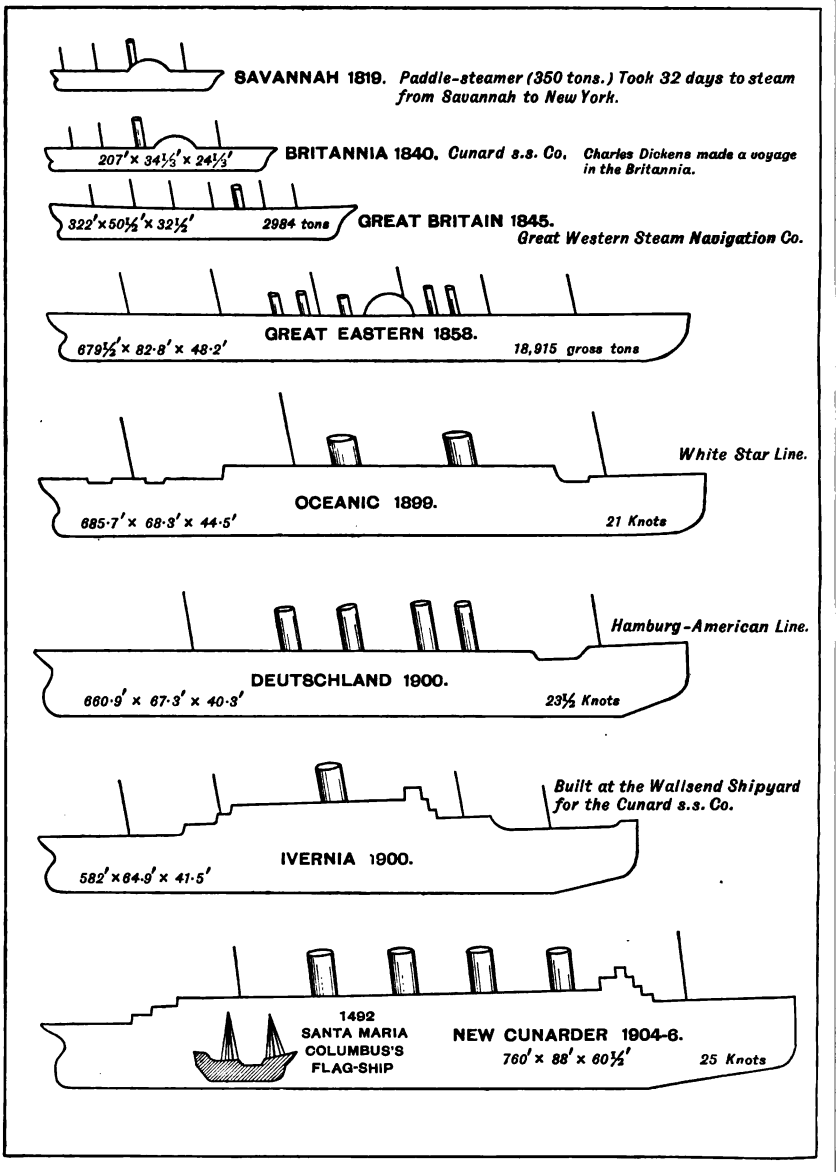


FIG. 57. TRANSATLANTIC VESSELS OF THE PAST AND PRESENT.

Reproduced from "The Mid-Tyne Link," Wallsend-on-Tyne. By permission of the Editor.

driven by the low pressure and the outer by the high pressure drums.

The enormous progress that is being made in this branch of science at the present day is aptly illustrated by the accompanying diagram (reprinted from the "Mid Tyne Link"), showing the increase in the size of trans-atlantic packets since the time of Columbus. Some further idea of the colossal nature of the new Cunard enterprise can be gathered from the facts that the combined I.H.P. of the main engines of the new ship reaches the hitherto unapproached figure of 70,000, that there are to be 23 double ended boilers and two single ended, and that the full boilers and engines will together weigh over 10,000 tons, and will consume about 1,000 tons of coal per day. A horse and cart could pass easily down either exhaust pipe.

CHAPTER VII.

THE DE LAVAL TURBINE.

WE notice a contrast very clearly defined when we turn from the turbine of Parsons to the second successful steam turbine of modern times. In 1883, De Laval, a member of the Swedish House of Representatives, and already well known as an inventor in connection with dairy machinery, first endeavoured to produce a rotary steam engine for the direct high speed driving of a churn. In the year 1889 he evolved the steam turbine known by his name, which has already achieved great popularity in its native country, and bids fair to be equally successful in America and France. The machine has only recently been introduced into this country, but there is every reason to suppose that its suitability for the driving of light machinery will meet with full recognition in the course of time.

This turbine is in every respect the direct antithesis of that of Parsons. The latter is a somewhat complex turbine of the reaction class, depending for its efficiency on the large number of expansions taking place within the turbine cylinder; the former is an impulse turbine, exceedingly light and simple in construction, developing the kinetic energy of the steam by a single expansion, and that not strictly within the cylinder at all.

The principle of the De Laval turbine is that of the

Pelton wheel; the detail of the arrangement is very different. The rotor itself consists of a single wheel of forged steel, very thick at the central boss, and tapering to the rim in the manner indicated in the figure. The

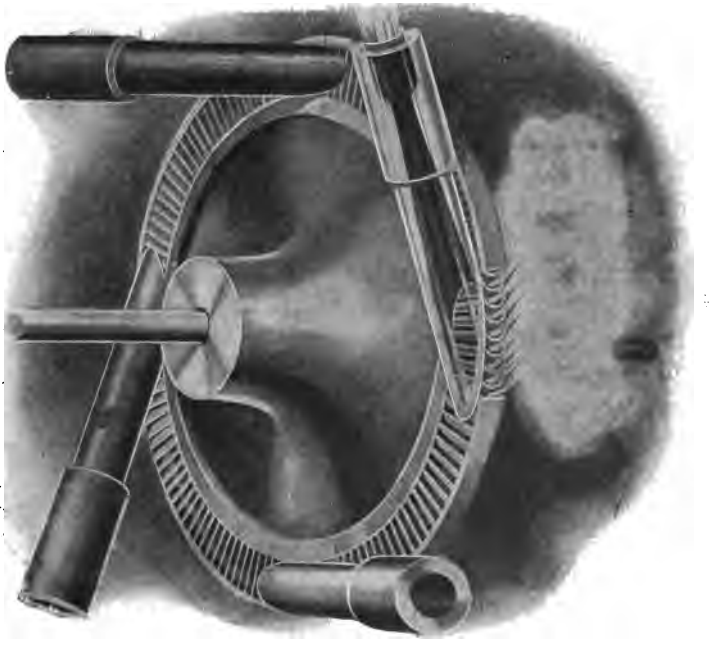


FIG. 58. THE DE LAVAL WHEEL.

diameter of the wheel varies from 4 to 30 inches, according to the power of the turbine. The blades are not unlike those of the Parsons turbine in shape, but are considerably more curved, and are set symmetrically, otherwise than those of Parsons, in the plane of the wheel, both

edges being inclined at an angle of 30° to 45° to the direction of motion. These blades are dovetailed into the rim of the wheel in such a fashion that it is impossible to remove them by a direct outward pull, and the ends of the blades are flanged to form, when fitted together, a rim round the outside of the steam passages. Such blades are known to turbine engineers as buckets. The whole of the rotor is designed for the express purpose of withstanding enormous centrifugal forces, on account of the very high speeds at which these wheels are run.

Steam enters the wheel from a nozzle or nozzles inclined to the plane of the wheel at an angle of 20°. The form of this nozzle (patented in 1889), is the sum and substance of De Laval's invention.

In order that the action of the turbine may be efficient, it is essential that the velocity at admission should be as great as possible. Now, if we were dealing with water, this condition would be sufficiently ensured by the mere fact that there is no back pressure, and the velocity would depend only on the pressure behind the jet. In dealing with steam, however, we have the elasticity of the fluid to consider, and some interesting physical conditions result.

If boiler steam be allowed to escape, either through a hole in a plate or through such a nozzle as we have described in connection with the Pelton wheel, it will be found that, after issuing from the restricting channel, the steam jet spreads out in every direction, so that it is not possible to direct it into a blade channel, as must be done in a turbine; neither is every part of the stream moving (as is required) in the same direction. This is only true in the case where the boiler pressure is more than double that of the medium into which the jet is

discharged, and the reason of the phenomenon is susceptible of a simple explanation (see App. III).

There is no simple relation connecting steam pressure with velocity developed, and the complicated formulae that have been suggested for the purpose will hardly be useful in our present investigation. We may illustrate the relation by saying that steam of 160 pounds pressure and 50° superheat will develop a velocity of about 1,450 feet per second on expansion to a pressure of 85 pounds, but will only develop a speed of 4,000 feet on expansion to a 26 inch vacuum. Now the section of a channel necessary to carry a given flow of steam is inversely proportional to the velocity of the jet, and directly proportional to the volume of a given weight of the vapour. If, then, steam is being blown off from a chamber in which the pressure is 160 pounds and the superheat 50°, the section of channel necessary to discharge the steam occupying 1 cubic foot of the reservoir in one second will be $\frac{1{\cdot}70}{1{,}450}$ square foot (or 0·169 square inch) if the discharge is to take place at a pressure of 85 pounds, but will be $\frac{70}{4{,}000}$ square foot (or $2\frac{1}{2}$ square inches) if the discharge is to take place at a pressure of 2 pounds absolute. If, on the other hand, the pressure in the orifice of discharge were 140 pounds, the velocity of discharge would be 660 feet per second, and the volume would be increased by 10%, so that the necessary section would be $\frac{1{\cdot}10}{660}$ square foot or or 0·24 square inch.

In the same way we could find the necessary orifice of discharge for any pressure within the neck which we might care to assume, and it would appear at the end that the smallest aperture is arrived at with pressure of

about 85 pounds. This, then, is the pressure which steam would naturally possess in escaping through a simple orifice from a boiler in which the pressure was 160 pounds. If we adopted, in a steam turbine working at this pressure, the nozzles described earlier in connection with the Pelton wheel, the steam would pass through these nozzles at the pressure of 85 pounds, and would then expand in every direction into the vacuum or atmosphere, instead of continuing in a straight line as the water does.

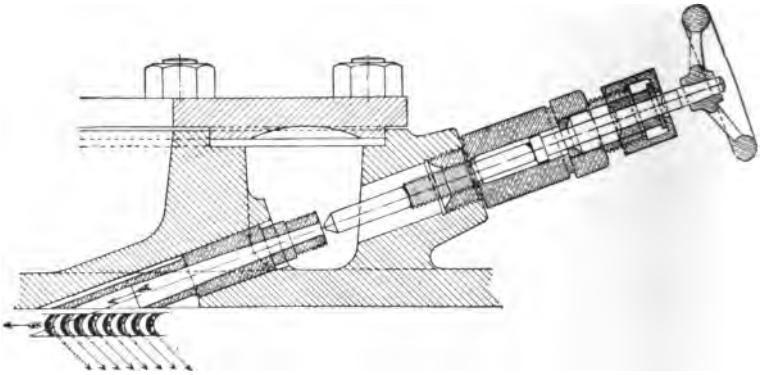


FIG. 59. DE LAVAL NOZZLE AND BLADES.

To prevent this bushing out of the steam at the mouth of the nozzle, De Laval—and herein lies his invention—adds to the simple nozzle an expanding cone (Fig. 59). Now when the steam expands laterally, after passing through the neck, it meets the conical surface and is reflected into the desired direction. All the steam, therefore, passes along the funnel, increasing rapidly in volume and more slowly in velocity.

The size of the neck regulates the amount of steam used, and adjustment is made by a needle as in the Pelton nozzle. Suppose that the section of the neck is

0·169 square inch. One cubic foot of boiler steam is discharged per second. In order that the steam may not diverge on leaving the funnel, it is necessary to prolong the cone until the steam flowing through it attains the pressure prevailing in the turbine case. If this is equivalent to a 26 inch vacuum, the final section of the cone must be $2\frac{1}{2}$ square inches, and the velocity of the steam impinging on the wheel will then be 4,000 feet per second. We have, therefore, the curious and superficially improbable truth that steam flowing in a diverging pipe increases in speed and falls in pressure, in precise contrast to the action of water under similar circumstances (App. II).

The number of nozzles used varies according to the size of the turbine. On the 300 H.P. machine manufactured by Greenwood and Batley, of Leeds, the largest standard De Laval turbine on the market, the number of nozzles used is 12, but the machine is capable of developing the specified power with only eight of them in operation.

We have seen that, under ordinary conditions, steam enters the turbine case at a speed intermediate between 3,500 and 4,000 feet per second, and therefore with a kinetic energy of 1/12 to 1/8 of a horse-power-hour per pound of steam. In order to communicate all this energy to the turbine wheel in a single passage, it would be necessary to run the wheel with a peripheral velocity of 2,000 feet per second, a speed at present unattainable. Neither is it possible to use the system of impulse of the Pelton and similar wheels without modification, as this would require buckets too heavy for the necessary speed of running (see page 192). Instead, the nozzles are set alongside of the wheel, inclined thereto at an angle of 20°, and bevelled off so as to come very close to the blades.

The fact that the steam does not approach the blades strictly in the direction of motion of the wheel would necessitate, for perfect efficiency, a blade velocity exceeding half the nozzle velocity of the steam; but the highest speed yet attained is considerably less, namely, 1,380 feet per second, the bucket speed of the 300 H.P. turbine. The diameter of this wheel is 30 inches, so that it makes 10,600 revolutions per minute.

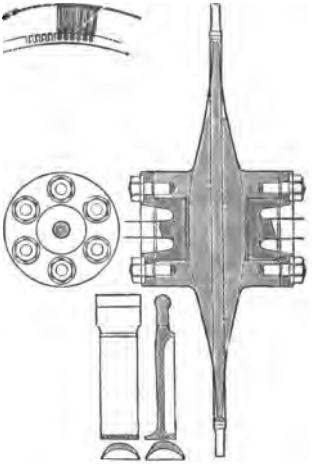


FIG. 60. WHEEL OF LARGE DE LAVAL TURBINE, BLADES ENLARGED. (GREENWOOD AND BATLEY.)

Suppose that steam enters the wheel case at the somewhat excessive speed of 4,000 feet per second. We can show geometrically (App. I) that it has a speed of about 2,800 feet relative to and along the blades; and it follows that the steam is discharged with an absolute velocity of 2,000 feet per second, one half the speed of admission. The proportion of energy carried off by the steam is then $\frac{1}{4}$ of the whole, and that communicated to the wheel is the remaining $\frac{3}{4}$, or 3/32 of a

H.P.-hour per pound of steam. Allowing, therefore, nothing whatever for resistance of wheel passages or nozzles, for impact and resistances of bearings or gearing and the like, we may say that the theoretically perfect De Laval turbine, running under these conditions, should show a steam consumption of 10·66 pounds. per H.P.-hour. It speaks very highly for the construction of this turbine that there should have been obtained, throughout a prolonged test of a 300 H.P. machine, running with eight nozzles at 352 H.P. a steam consumption of 13·94 pounds per H.P. hour.

The foregoing discussion of the theory of De Laval's turbine sufficiently indicates that the most notable feature of the machine, in practice, is its extraordinarily high speed. The speeds of the types now on the market vary from 10,000 to 30,000 revolutions per minute, and every part of the rotor must be designed to stand the stresses arising from this cause.

Let us consider for a moment the 300 H.P. model. The weight of one of the buckets is 1/28 of a pound, its length is $1\frac{1}{2}$ inch, and it is dovetailed into the rim of the wheel. The mean velocity of the blade is 1,380 feet per second, more than half the speed of a rifle bullet, and the stress on the inner end is therefore $\frac{1}{28} \times \frac{1380^2}{32 \times 1\frac{1}{4}}$ lb. ($1\frac{1}{4}$ foot being the radius of the path of the blade), which reduces to $1{,}562\frac{1}{2}$ pounds, or nearly 14 cwt. The cross section of the blade is about ·045 of an inch, so that the stress works out at nearly 16 tons to the square inch.

We have seen that some of the fast-running water turbines have a steel tyre outside the blades to guard against their being drawn. It is hardly necessary to point out that no steel tyre could stand the strain created by a velocity of 1,410 feet per second, or 960 miles an hour,

that of the outer ends of these blades. The whole stress is therefore carried by the dovetail joint, and is added to the other stresses within the wheel itself. These stresses increase rapidly as we pass inwards from the rim, and the thickness of the wheel is increased correspondingly. The curve formed by a section of a wheel of maximum lightness and strength, is the solution of a differential equation, which will afford a pretty problem for the ma-

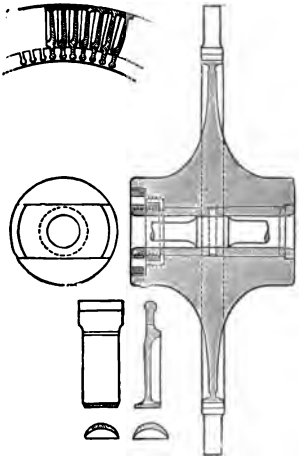


FIG. 61. WHEEL OF SMALL DE LAVAL TURBINE SHOWING FLEXIBLE SHAFT. (GREENWOOD AND BATLEY.)

thematical reader. The best assumption to make will be that the stress is to be 12 tons to the square inch *in every direction* in the plane of motion throughout the structure of the wheel.

It is clear that in a solid wheel the stresses across the centre will be considerable. If the central part is cored out to make room for the axle, the hub must be made very heavy to supply the strength lost from this cause. It will be noticed that the axle of the 300 H.P. turbine is fitted without coring the wheel (Fig. 60).

The axle itself is one of the most remarkable parts of the machine, and exemplifies another very pretty mathematical problem. Owing to the high speed, the shaft has no great torque to bear (it is only 158 pound-feet in the largest machine, and the five-horse wheel gives 0·875 pound-foot only). A stout shaft is therefore unnecessary. If, however, a thin shaft be used, it will be necessary to consider the possible effects of want of balance on its rectitude.

The strain which we found to exist on the buckets sufficiently indicates the stresses that might arise from any want of balance in the rotating parts, and, since an error of one ounce might cause a rapidly alternating load of one ton on the bearing, it is clear that some measures must be taken to prevent the racking of the machine to pieces. Parsons used a floating bearing for his earlier turbines: De Laval has adopted a flexible shaft.

The shaft of the 150 H.P. turbine is only one inch in diameter, and the bearings are set at a distance from the wheel rather greater than the radius. The shaft is therefore an elastic rod loaded at the centre, and if displaced it will vibrate in the same fashion as the reed of a trumpet, having a definite period. Now, if there is a slight want of balance in the turbine wheel, the centre of gravity being at a small distance, A, from the centre of the shaft, the shaft will be always pulled towards the centre of gravity, and if the speed of rotation be slow it will take a set in that direction, increasing still further the want of balance. The shaft, being bent in one direction, has a natural tendency to spring back and bend in the other; but the centrifugal force is being continually reversed as the wheel turns. As the rotation is accelerated, this reversal becomes more frequent until it coincides in period with the natural vibration of the shaft.

This is the critical speed, and if the wheel make many revolutions at this speed, the shaft is bound to break. To avoid this, safety bearings are provided close to the hub.

But the question of interest for us is this. "What happens when the speed of the rotor exceeds the critical speed?" The answer may be suggested by the familiar "cowboy" trick of spinning a lassoo in the form of a hoop by means of the rope attached to the circumference. When the critical speed is exceeded, the wheel turns and reverses the strain on the axle before that strain has had any appreciable effect; and, as the speed increases more and more, the force necessary to deflect the middle point of the axle through a distance of 1/100 of an inch or so, becomes practically negligible in comparison with the other forces in operation. The stiffness of the shaft can then be neglected, and it begins to fulfil the functions of the "cowboy's" rope, while the wheel turns about its own centre of gravity.

This very curious fact can be easily shown mathematically. Suppose that the deflection of the shaft is D *towards* the centre of gravity. The radius of the path of that centre is A+D, and the centrifugal force is $CN^2(A+D)$, while the elastic force on the shaft is B.D, where B and C are constants and N is the speed. If the motion is steady these forces must balance, and we have $CN^2(A+D) = B.D$, or $D = \frac{CN^2A.}{B-CN^2}$ It appears, then, that D, the deflection, is postive if $B-CN^2$ is positive, infinite if $B-CN^2=0$ (this gives the critical speed, $N=\sqrt{\frac{C}{B}}$), and negative if N has a greater value than the critical one. The greater N becomes, the more nearly D approaches the value $-A$, at which the centre of gravity of the wheel is its centre of rotation. The mathematician

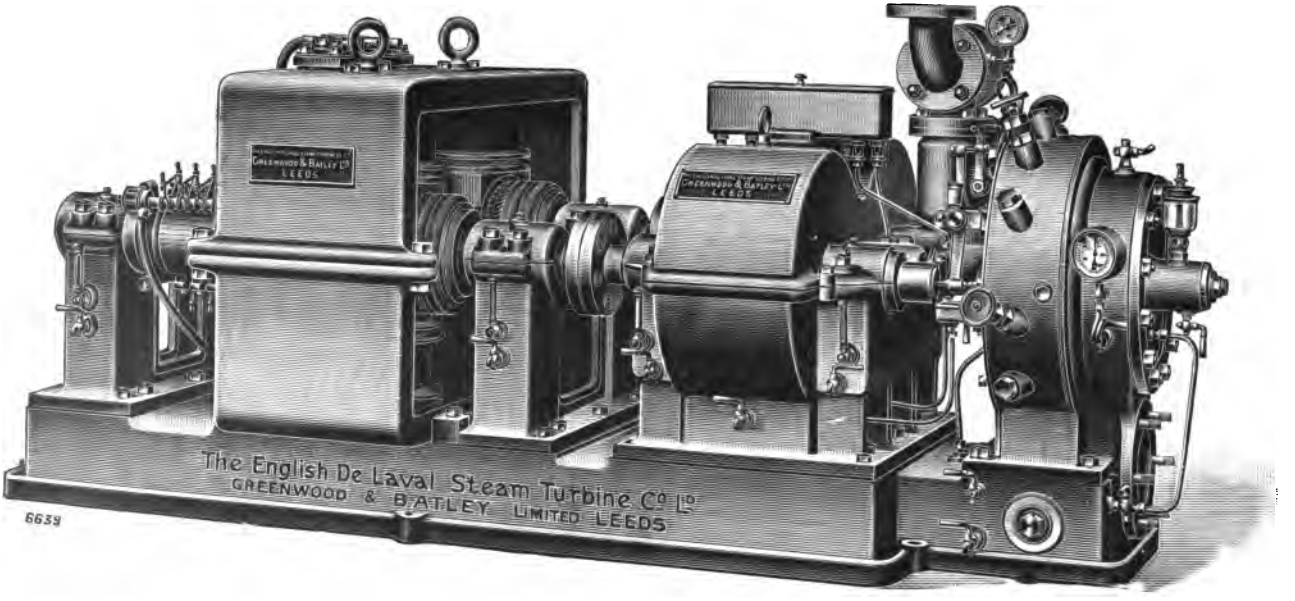


FIG. 62. 150 KW. DE LAVAL TURBO-GENERATOR.

or the draughtsman will find it at once instructive and interesting to sketch the curves traced by the vibrating shaft at different speeds of rotation. They can be mechanically shown by rotating a conical pendulum at various speeds and giving to it an oscillation at the same time. The ellipse corresponds to the critical speed.

The theory of the De Laval turbine is undoubtedly interesting. In practice it has attained a very fair efficiency, and has the merits of extreme lightness, compactness, and simplicity. The turbine, complete, with the necessary gearing for connection to machinery running at ordinary speeds, is far lighter and smaller than a reciprocating engine of the same power, or even than a petrol motor. The De Laval turbine is not likely in the near future to come into competition with other steam turbines, chiefly because it is most suitable for light work, and has never been applied to the development of power in excess of 300 H.P., the power at which the other forms of steam turbine begin to be efficient.

Of all the merits of the De Laval turbine the most conspicuous is its simplicity, arising from the fact that it is a single stage impulse machine. The position of the nozzles renders it impossible for the steam to do other than go through the wheel passages, and once it has done so, it is done with for the purpose of the turbine. Regulation is effected by a simple throttle with perfect efficiency. There is no close fitting anywhere, and no need for any. The engine requires no skilled attention, and it is a pity that its merits are not more fully recognized by small power users in this country.

The disadvantage of the turbine is that it is not possible to use the full power of the steam in a single wheel. To a certain extent the energy of the steam leaving the rotor can be used, in a properly constructed condenser,

to save the air pump, but the advantage is a small one. Suggestions have been made for the compounding of these turbines, but this can only be done by sacrificing to some extent the pre-eminent simplicity of the machine. There are two obvious ways of setting about it. The first is to expand the steam in two stages, with an intermediate receiver between the two wheels. This receiver may be simply the case of the first turbine. Whether a separate one is provided or no, the first wheel-case will in fact be full of steam at intermediate pressure, and this will cause a resistance to the motion of the wheel, which, in view of the high speed and slight torque of the wheel-shaft, is bound to produce a very serious loss.

According to the second system of compounding, the full expansion takes place in the nozzle, but the steam discharged from the wheel passages enters fixed passages or ports, by which it is conducted to other wheels on the same shaft; but this involves the complete sacrifice of the simplicity of the old machine, and creates a turbine of greater efficiency, power and complication, to which we must devote another chapter. But before we turn our attention to these compound turbines, we must notice the other simple impulse turbine, in some respects the most extraordinary steam engine yet produced.

The Riedler-Stumpf steam turbine, which is considerably used in Germany for small installations, and of which there is at least one large specimen in existence, the 2,000 kw. turbine at Moabit, is practically a Pelton wheel. It is necessary, as in the De Laval turbine, to attain a very high bucket speed, but this is done by using a large wheel, which runs at the comparatively moderate speed of 3,000 to 4,000 R.P.M. The diameters of the wheels vary from 5 to 10 feet.

At the high speed used, great strength and perfect

balance are necessary in the rotor. These are attained by forming the wheel of a single piece of very hard nickel steel. The pockets are cut out of the wheel, and differ

FIG. 63. ROTOR OF RIEDLER-STUMPF TURBINE.
(ALLGEMEINE ELEKTRICITÄTS GESELLSCHAFT, BERLIN.)

from Pelton buckets in that they are open only at the sides, for the purpose of discharging steam. It is possible, therefore, to collect the exhaust steam and to compound the turbine by re-using it. This has been done in some

cases, and the steam is returned either to another wheel on the same shaft, or else to the same wheel, as was done in the turbine shown in Fig. 36. These machines are, however, very seldom compounded.

The nozzle is set in the plane of the rotor, as is the nozzle of a Pelton wheel, but, of course, a divergent instead of a convergent mouth is used. On account of the difference in the working fluid it becomes important to

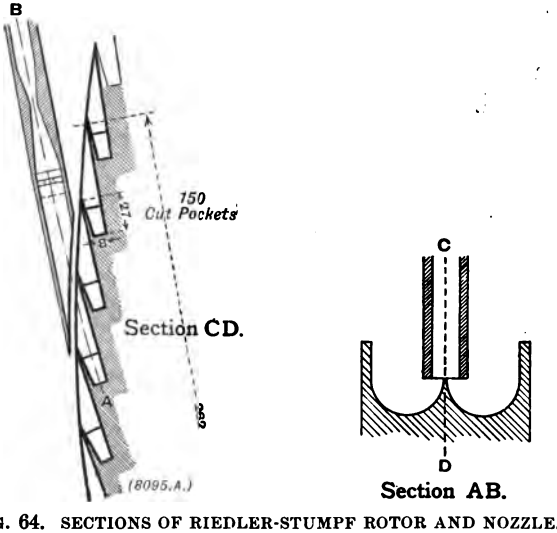


FIG. 64. SECTIONS OF RIEDLER-STUMPF ROTOR AND NOZZLE.

have the nozzle close up to the pockets into which it discharges. The greatest clearance permissible is a quarter of an inch. The nozzle is therefore bevelled off like that of De Laval, and fits closely outside the wheel (Fig. 64). The flexible shaft is now out of the question—the rotor is too heavy for its use in the first place, and, in the second, play is undesirable. The smooth running of the wheel depends, therefore, entirely on the accuracy of the turning and the care with which the pockets are cut.

Very fair results, so far as steam consumption is concerned, have been obtained with this turbine, the best result showing a consumption of 19½ pounds of steam per kilowatt-hour (equivalent to about 13½ pounds per B.H.P.-hour) obtained with the 2,000 H.P. turbine before referred to, running at rather less than full load. The engine shares the peculiarity of all the Pelton wheels, that the highest efficiency is obtained when the load is below the normal figure, in contrast to the Parsons, and to most other steam turbines, which show their mettle on an emergency, that is to say, when considerably overloaded.

CHAPTER VIII.

THE CURTIS AND OTHER IMPULSE TURBINES.

WITHIN the last few years a large number of new steam turbines have been produced by various manufacturers, for the most part in Germany; and these differ one from another in different degrees, but they have this feature in common, that nearly every one is of the compound impulse type. The Schultz turbine, the only other reaction turbine on the market besides that of Parsons, differs from the latter so little as not to require a separate discussion in these pages.

The compound impulse turbines, however, though of very recent invention, have already considerable reputation both in Europe and in America, and have achieved excellent results in trials of reliability and economy. The last of these machines to have been put forward, that manufactured by the Allgemeine Elektricitäts Gesellschaft, of Berlin, appears, curiously enough, to be the simplest of them all. The smaller of these machines have, like those of De Laval, only a single pressure stage. The full velocity of the steam is therefore developed in the nozzle, but this velocity is used and destroyed, not in passage through a single moving bucket row, but by a series of actions on successive buckets, usually three in number. The small A.E.G. turbine is, therefore, to all intents and purposes, a modification of the early engine

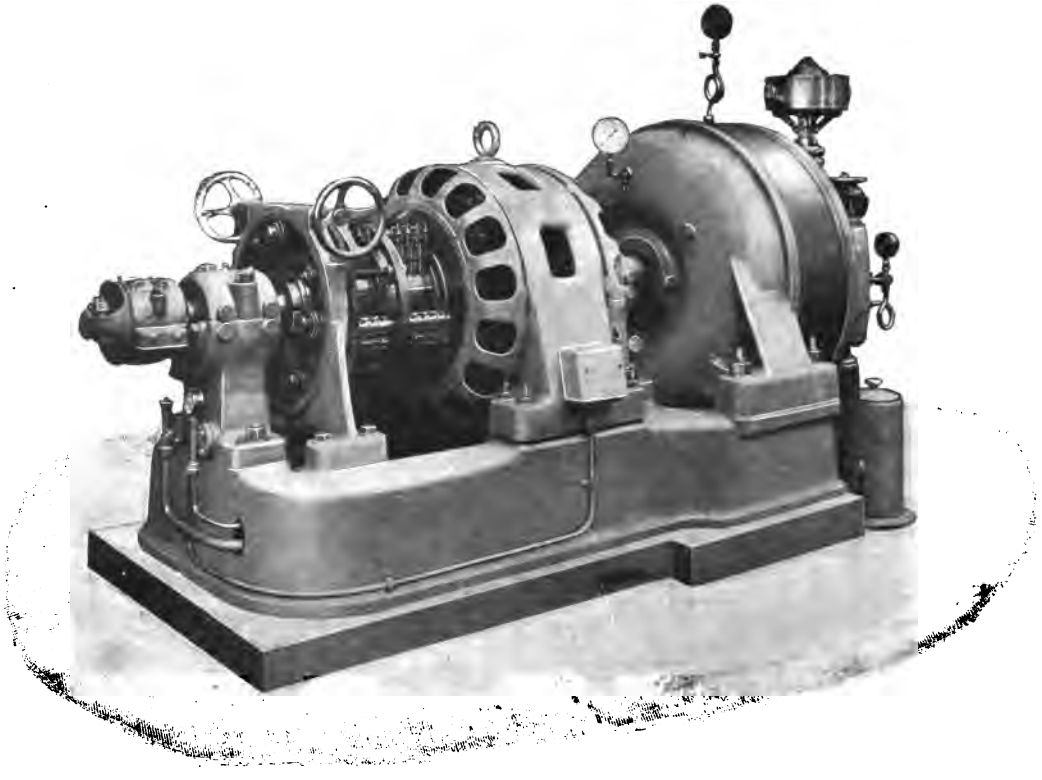


FIG. 65. 250 KW. A.E.G. TURBINE. (THE ELECTRICAL CO., LTD.)

of Harthan (Fig. 36) with the combination of De Laval's expanding nozzle.

The turbine is mounted on a horizontal shaft (Fig. 65), and directly coupled to the generator. The efficiency is fair, and the speed seems very moderate, when compared with that of the simple De Laval turbine; but the A.E.G. is not much used for the small powers which the latter engine has developed with so much success.

In large A.E.G. turbines a second pressure stage is introduced, and the action becomes very similar to that in the earlier Curtis turbine; the two differ principally in the manner of erection, the Curtis having a vertical, and the A.E.G. a horizontal axis. The best recorded test of the A.E.G. turbine shows a steam consumption of 16·6 pounds per kilowatt-hour, as against a corresponding figure of 15·8 pounds for the Curtis, which appears therefore to merit the greater attention.

* * * * *

The first patent for the Curtis turbine was taken out in the year 1895, and, since the machine was put on the market, some four years later, its merits have gained wide recognition in America, though it still appears to be little known in this country. The turbine cylinder, which has a vertical axis, is divided by horizontal diaphragms into a series of chambers, usually three or four in number, and in each chamber there are one or more rotating wheels carrying rows of buckets. There are usually two or three such rows in each chamber, and the older practice was to cut each set of channels out of a separate disc of solid steel (Fig. 66), so that there would be a number of such discs or wheels in each stage chamber. The speeds of running have, however, now been reduced, and it is therefore found practicable, and more advantageous, to cut the channels out of steel seg-

ments, and to bolt these segments on to the wheels, so as to form one or more complete circles of buckets on each wheel.

Between these moving bucket rows fixed buckets are

FIG. 66. SOLID STEEL ROTOR WHEEL OF CURTIS TURBINE, BLADES PARTIALLY CUT. (BRITISH THOMSON-HOUSTON CO., LTD.)

attached to the walls of the turbine cylinder. These are cut, like the moving ones, out of steel segments; but, since admission to the turbine is by nozzles, and round only a part of the circumference, it is clearly unnecessary that the fixed buckets should form a complete circle. Both fixed and moving buckets are of much the same

shape as those in a De Laval turbine, and the action in each stage chamber is, therefore, practically that suggested by Harthan in 1858. Admission to the first chamber is by nozzles set in the top of the turbine cylinder. These are grouped together, and are of a modified De Laval shape, permitting a partial expansion of the steam. Groups of passages of similar shape are cut in the diaphragms separating the stage chambers (Fig. 67), and it is in these passages that the expansions take place. The

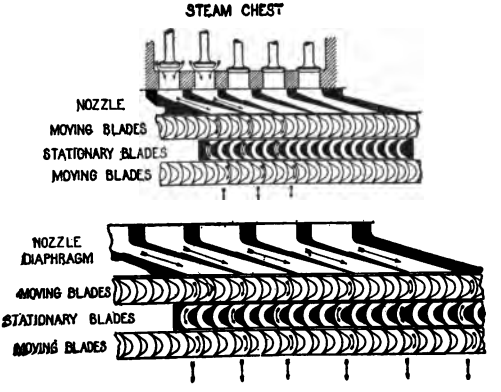


FIG. 67. DIAGRAM OF BLADES AND NOZZLES IN 2-STAGE CURTIS TURBINE. (B. T. H. CO.)

full velocity of each expansion is developed in the corresponding passage, and the action on the fixed and moving blades is purely impulsive. It is clear that groups of nozzles must be set diametrically opposite to one another, in order that the action on the rotor should be a pure torque.

We have already pointed out that there may be one or more wheels in each stage chamber. The group of wheels forms the rotor, which carries, therefore, a number of rows of buckets, somewhat unevenly spaced,

as, between some, small gaps are left for the fixed bucket rows, and, between others, larger gaps for the nozzle diaphragms. The external diameter of the whole rotor is uniform (Fig. 68), so that the speeds of all the buckets are the same, and the action in each stage chamber should, therefore, be identical, in spite of the changed volume of the steam. The solid discs forming parts of

FIG. 68. ROTOR OF 4-STAGE CURTIS TURBINE. (B. T. H. CO.)

the wheels are largest at the end of each stage-chamber nearest to the admission nozzles, so that those steam channels through which the flow takes place more slowly are deeper than the earlier ones.

From the uniformity of the bucket speed throughout the turbine, it follows that the steam velocities in each stage should be the same. The total velocities developed in each set of nozzles should, therefore, be equal, and

this requires the same ratio of expansion in each nozzle. If the pressure in the steam chest be 160 pounds, and if there be three stages, then, assuming a reasonable superheat, the pressure in the first two stage chambers should be approximately 40 pounds and 9 pounds respectively, while that in the last chamber will be the condenser pressure, say $1\frac{1}{2}$ or $1\frac{3}{4}$ pound per square inch absolute. The nozzles of each stage will then be much shorter than those in the De Laval turbine, having in fact a divergence of 40%, and the velocity developed in each nozzle will be about 2,500 feet per second.

FIG. 69. INSIDE OF 4-STAGE CURTIS TURBINE CYLINDER SHOWING FIXED BLADE ROWS. (B. T. H. CO.)

The inclination of each nozzle to the plane of the wheel is about 20°, and if the bucket velocity be 480 feet per second, the velocities of the steam at discharge from the first and second rows respectively will be approximately 1,600 and 750 feet per second. Since the work done on any bucket-row is equal (neglecting frictional losses) to the difference between the energies of the steam when entering and when leaving the buckets, the duties of the two rows in the first stage chamber will be in the ratio 37 : 20. The mass and velocities of the steam in the second stage chamber will be exactly the same as in the first, when running at full load, and

therefore the work done by each wheel in the second chamber is the same as that done by the corresponding wheel in the first. The volume of steam in the second chamber is, however, four times greater than in the first, and, therefore, the section of steam passage must be increased in the same proportion.

FIG. 70. LOW PRESSURE DIAPHRAGM OF CURTIS TURBINE SHOWING NOZZLES.

It is clear that, since the admission nozzles extend only round a part of the rim, some only of the wheel passages in the first chamber are in operation at a given moment. The diaphragm nozzles, however, extend round a larger arc, so that a larger number of the blades in the second chamber are under steam. The last row of diaphragm nozzles extends usually round the greater part of the circumference (Fig. 70). It is not, therefore, necessary

to increase the length of the buckets in this turbine in the same proportion as in that of Parsons, although the ratio of expansion is equally great.

The high steam velocities used in this turbine, and the great pressure on the blades of the first wheel in each stage chamber, make it probable that a large proportion of the losses in the turbine cylinder is due to steam friction on the guides and blades. This will be greatly increased if any water is present in the steam, and the advantage of superheating is consequently great. It appears that the best results as yet obtained from a 1,500 kw. Curtis turbine show a steam consumption of 15·8 pounds of steam, at a pressure of 200 pounds per square inch and 150° superheat, per kw.-hour, as against a consumption of 15·4 pounds by a 3,500 kw. Parsons turbine with the same superheat, and 18·5 pounds with a De Laval, developing 250 kw. under rather less favourable conditions.

It will be seen that the steam consumption of the Curtis turbine compares favourably with that of the best triple expansion engines, but is slightly inferior to that of a Parsons turbine; it must, however, be remembered that the Curtis machine is still in its infancy, and, thanks to the enthusiasm with which it has been taken up in its native country, is being rapidly developed and improved, so that an increased efficiency may be expected in the future.

We have pointed out that the chief burden of the work is borne by the first bucket row in each chamber. The effect of closing one or more of the admission nozzles on the distribution of duty is worth noting. The pressure in the first steam chamber falls to a certain extent, and the velocity in the diaphragm nozzles drops correspondingly, while that in the admission nozzles increases. The result

of this is a slight overloading of the wheel or wheels in the high pressure stage, the duties of the different rows becoming more evenly distributed than before. The load

FIG. 71. 1,100 KW. CURTIS TURBINE AND CONDENSER. (B. T. H. CO.)

in the low pressure stages diminishes to a corresponding extent.

If we overload the turbine by opening more than the normal number of admission nozzles, the brunt of the overload will be borne by the low pressure stages. On

the other hand, it will be found that any increase in the speed of the turbine tends to overload the high pressure stage and particularly the first bucket row, but a diminution in speed puts the load on to the final stages and equalizes the distribution between the different rows.

The Curtis, like the Parsons turbine, is capable of benefiting to the full by a good vacuum, and it is, therefore, usual to set the condenser immediately underneath the turbine, which exhausts through the floor of the engine room. The machine has hitherto been used almost exclusively for the driving of dynamos, and has been made in all sizes from 1½ to 5,000 kw. Direct driving is usual. The field magnets of the dynamo, in the large polyphase machines (in others the armature) are keyed to the turbine shaft immediately above the steam inlet. The fixed armature (or field magnets) rests on the turbine case.

The weight of the whole rotor of engine and dynamo is carried by a very simple and most ingenious bearing, suggestive of the mercury bath used in lighthouses. This bearing consists of a cast iron shoe on the shaft, resting on a cast iron step, and surrounded by a ball race to preserve the centring. The step is made slightly concave and is fed with high pressure oil, so that the moving parts float freely on the lubricant. The bearing is entirely external to the turbine case, and contamination of the steam is impossible.

The permanence of adjustment secured by this simple and effective device makes it possible to run the turbine with very small clearance between the fixed and moving buckets. It is important that this clearance should be as small as possible, and the large diameter of the rotating wheels makes the rigid bearing an essential feature of the machine. It is perhaps for this reason that the

Curtis turbine has not yet been successfully applied to marine propulsion, which requires a horizontal axis of rotation.

The Curtis turbine, like that of De Laval, operates very economically with low boiler pressures, which would be unsatisfactory for a reciprocating engine, and it is possible that a Curtis turbine of two or three blade rows might be advantageously used to replace the low pressure cylinder in a compound or triple expansion engine, or to develop the energy of the steam exhausted from a reciprocating engine of the simple or compound type. It must, however, be borne in mind that a good vacuum is essential for the satisfactory operation of the machine, particularly if the initial pressure be low.

* * * * *

Intermediate between the Curtis and the Parsons turbines in the nature of their action are the less well known Zoelly, Rateau, and Schultz turbines. None of these turbines have as yet equalled the former two machines in efficiency, while all of them run at speeds rather higher than that of the Curtis. The Schultz in fact requires a speed considerably in excess of that of the smallest of Parsons' turbines for the economical development of power.

Of all these machines, that which approaches most nearly to the Curtis in the nature of its action is the Zoelly turbine. This is also a pure impulse turbine, but differs from that of Curtis in the fact that expansion takes place in each fixed blade row instead of in the nozzle row only, and the steam leaves each rotating row almost entirely deprived of velocity. This necessitates a modification in the form of the fixed guide blades. While the moving blades in the Zoelly turbine are practically identical in shape with those of the Curtis, the

fixed blades (*m*, Fig. 72) approach much more nearly in shape to those of the Parsons turbine, or of the Jonval water turbine previously discussed.

We have explained in Chapter II that a turbine in

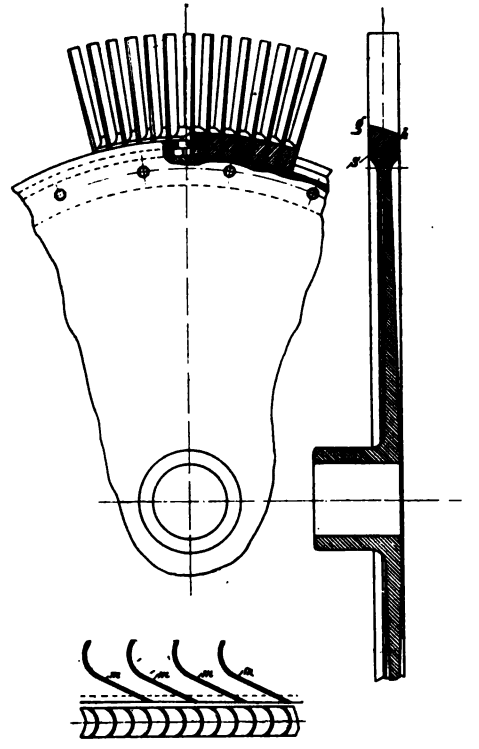


FIG. 72. BLADING OF ZOELLY TURBINE. (ESCHER WYSS AND CO.)

which the pressure drops in successive stages will need many more blade rows than one in which the full velocity is developed by a single expansion, or else must run at a higher speed. It will, therefore, be readily understood that the Zoelly turbine has need of more stages

than the Curtis. There are 10 wheels (Fig. 73) in the Zoelly turbine as originally produced, each of these differing from the Curtis wheels chiefly in carrying only one blade row, the blades being inserted in a T-shaped slot, and not surrounded by a rim, like the Curtis buckets. The shaft of the Zoelly turbine is horizontal, and the clearances are rather greater than in the Curtis machine. The speed of running is also greater. To secure the necessary rigidity, the case is divided into two parts between which there is a bearing, so that the shaft has three points of support.

The admission to this turbine takes place all round the wheel, as in that of Parsons, and not by means of nozzles. The speeds of running are also approximately those of the smaller Parsons machines, and considerably in excess of those favoured by Curtis.

Tests show a steam consumption slightly in excess of 18 pounds per kw.-hour, but there is little doubt that the engine, which appears to have many features of exceptional merit, will be made more efficient after further experiment. The Zoelly turbine has been fitted to Swiss lake steamers with some success.

The Rateau turbine differs very slightly from that of Zoelly. The rotor blades are flatter, and are riveted to the wheels, and admission is partial, by nozzles, as in the Curtis. The flatter blades make a greater number of stages necessary in the Rateau than in the Zoelly turbine, but a lower speed of running is secured. This turbine has been found very successful when running under a low steam pressure, and its possibilities as a utilizer of exhaust steam from reciprocating engines deserve the attention of power consumers.

The Schultz turbine differs from that of Parsons in no important particulars except its shape. The inventor

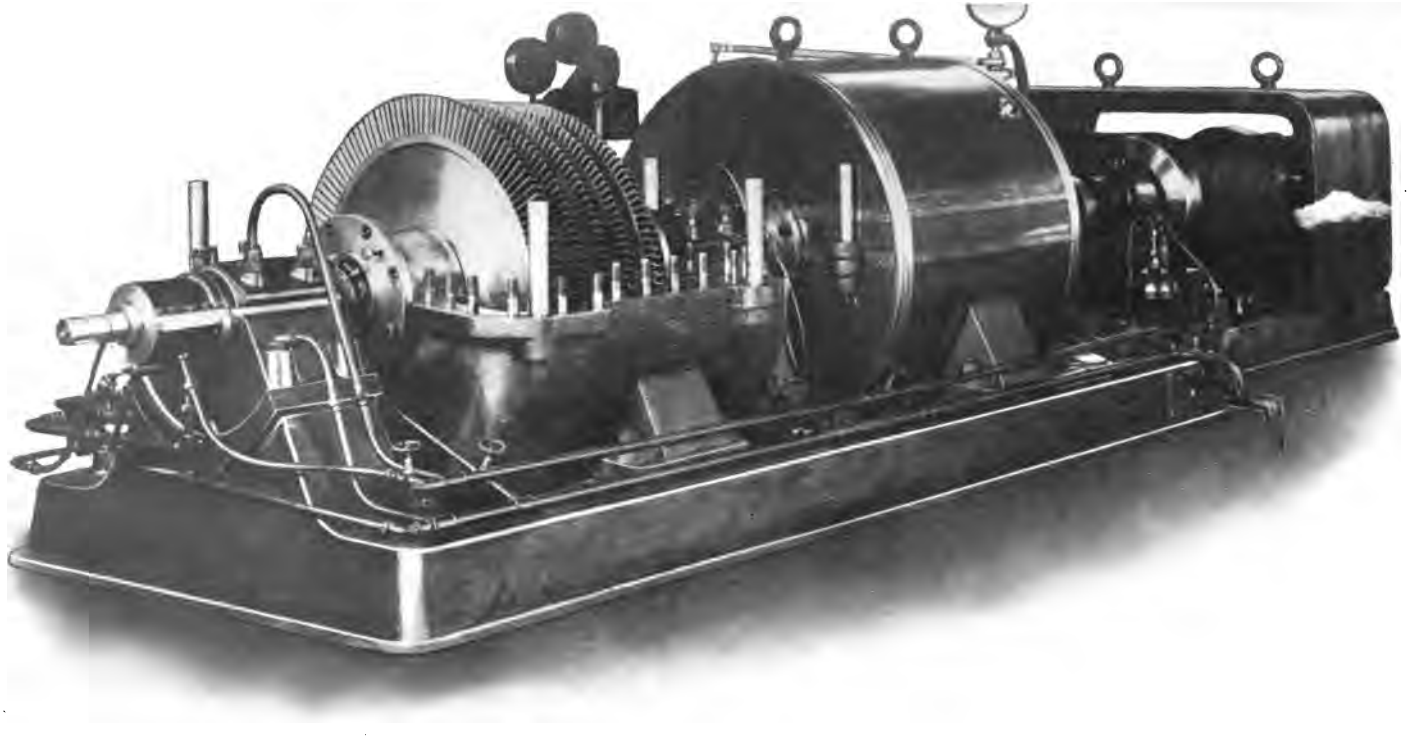


FIG. 73. ZOELLY TURBINE WITH COVER OF LOW PRESSURE CYLINDER REMOVED. NOTE THE INCREASED LENGTH OF BLADE NEAR THE EXHAUST. (ESCHER WYSS AND CO.)

abolishes the rotating pistons by which the equilibrium of the Parsons shaft is secured, and sends the steam instead in opposite directions along the high and low pressure cones, which compose its rotor.

Nearly all the Continental turbines have been tried in the German navy, apparently without much success, though no results have hitherto been published. It is rumoured that the Parsons turbine is now about to be adopted by the Imperial Navy to a very great extent.

Another reaction turbine that deserves mention on account of the extreme originality of its design is the Gelpke Kugel. This is a compound radial turbine of the reaction type. The steam expands in a large number of stages, flowing alternately outwards and inwards, and the blade designs of the outward and inward flow sections of the machine are very similar to those in the water turbines of Fourneyron and Francis respectively. The speed of the shaft is high, and control is effected by adjustment of the guides on the system common in Francis turbines. This, like many similar machines, is still somewhat experimental.

UNIVERSITY OF CALIFORNIA

CHAPTER IX.

TURBO-BLOWERS AND ROTARY PUMPS.

THE mere fact that an engine is driven by the pressure of an expanding gas naturally suggests the idea that, by a reversal of the process, the engine might be used for the compression of a fluid. It is probably fair to assume that the reciprocating engine was first suggested by the older force pump; indeed, except in the arrangement of the valves, the two machines are mechanically identical, and the effect of compelling such an engine, fitted with a slide valve, to run in the opposite direction to that for which the valves are set, would be to pump air into the boiler.

In the consideration of the engines of which we have been treating in this work the question naturally arises as to how far the turbine can be used by reversal as a force pump or as an air compressor. It is clear that when a fluid presses on a piston there are equal and opposite forces exerted between the two parties to the action, and that which advances does work on that which retires. The action is therefore perfectly reversible. On the other hand, when a fluid acts on a blade not by reason of its static pressure, but because the blade is curved and the fluid rushes quickly round the concave surface, then the action depends on the fact that the fluid is streaming past the blade, and is not reversible.

We are therefore in a position to give a general answer to the question just stated in these terms:—

A reaction turbine may be reversed so as to act as a force pump or air compressor, but an impulse turbine cannot.

The fact that a reaction turbine is reversible had been discovered as a matter of engineering practice before it had occurred to any theorist to question whether it was so or not. The first centrifugal pump was constructed by Appold in 1851, and is in all essentials the same engine as the vortex turbine or case wheel patented by James Thomson in the previous year. Within the wheel of this pump there is a forced vortex (App. II), and the nature of the action has already been fully discussed in connection with the casewheel (Chap. VI). In this discussion we pointed out that the flow through the case wheel would cease if the speed at the circumference were that due to half the head (or rather greater than that, since the blades do not reach the centre of the wheel). If now the guides were reversed and the turbine run at a slightly greater speed, it would begin to act as a pump.

The speed at which such a pump must be run in order to raise water to a given head can be easily found. If the speed of the outer rim of the rotor be V and that of the inner rim U, then the pressure of the water at the outer rim is V^2-U^2, that due to a head $\frac{V^2-U^2}{2G}$, and the velocity of this water is V, that due to a head, $\frac{V^2}{2G}$. The sum of the pressure head and velocity head of the water at discharge from the wheel make up the total head, or the height to which it can rise if there be proper guide blades to utilize the velocity possessed by the water. The speed necessary to raise water to a height H is therefore given by $V^2/2G+(V^2-U^2)/2G=H$.

Now, if the outer radius be R, and the inner radius R', and if the speed be N revolutions per minute, then $V = N \times R \times 0{\cdot}105$, and $U = N \times R' \times 0{\cdot}105$, so that we have $N^2 \times 0{\cdot}011 \times (2R^2 - R'^2) = 2GH$.

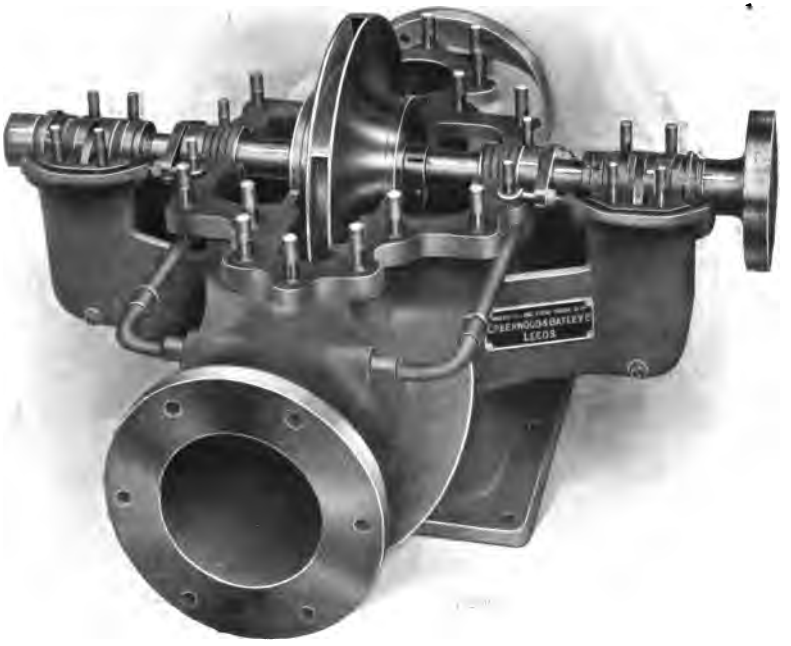


FIG. 74. HIGH SPEED CENTRIFUGAL PUMP.

It is clear from the above work, and indeed it is pretty clear without any mathematical analysis, that the speed of a centrifugal pump must in any case be large. As a matter of fact the blades of the wheel (Fig. 74) are not perpendicular to the rim at their outer ends, as are those of the case wheel, and consequently, when there is a large

flow the water has considerable velocity along the rotor blades, and its pressure and velocity at the rim of the wheel are less than they would be if the blades were radial. It follows that the speed must be more than that found above, so that very high speed driving is necessary if the head to be overcome is at all a large one.

In the case of a pump wheel of diameter two feet, to which water is admitted through an orifice of 6 inches diameter, the maximum head resulting from a speed of 1,000 revolutions per minute, would clearly be $1{,}000{,}000 \times 0{\cdot}011 \times (2-1/16) \div 2G$, or 330 feet. If the pump were to act against this head there would, of course, be no flow at all, so that such a pump would be best adapted in practice for a head about 20 per cent. less, that is a head of 264 feet, or 115 pounds per square inch. This is about the maximum head for which a simple centrifugal pump will be found suitable. Messrs. Escher Wyss and Co. have constructed some multiple centrifugal pumps, with alternate stationary and rotating disks, by which water is raised to a head of 500 lb. to the square inch. The economy of these turbo-pumps appears to be superior to that of most of those of the reciprocating type.

For this driving, turbines are pre-eminently suitable. The makers of the De Laval turbine, in particular, have devoted a good deal of attention to the production of turbine driven pumps for feeding boilers and for other high pressure work. A centrifugal pump designed for connection to a De Laval turbine is shown in Fig. 75. The speed of this machine is about 1,100 revolutions per minute, a speed at which rope or belt driving is wasteful and difficult, and direct connection to anything but a steam turbine or electric motor almost impossible. It will be noticed that the wheel in the figure is set in a volute or spiral case, so that the speed of the water

leaving it is used and the stream deflected into the discharge pipe.

Similar machines have been in use as centrifugal air blowers for many years. A great variety of blade forms

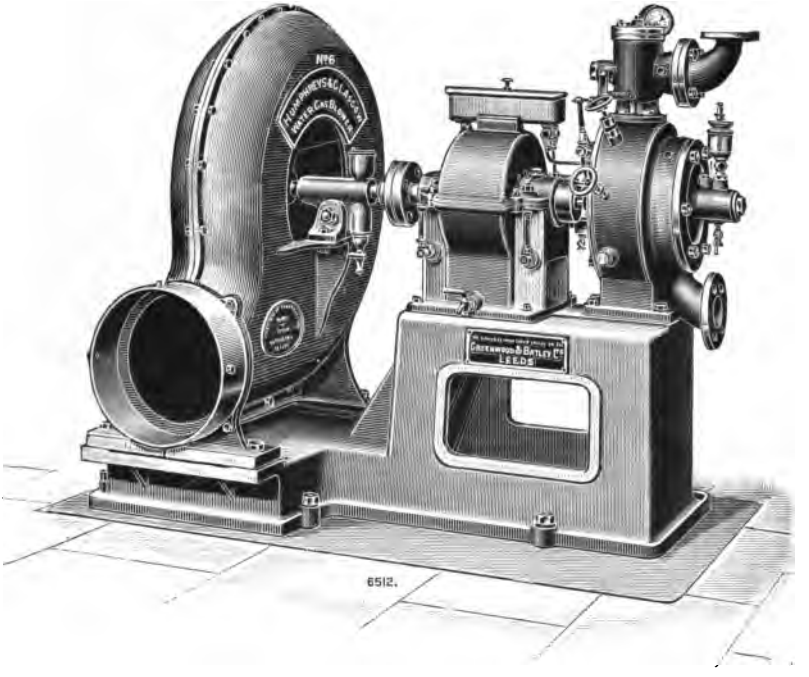


FIG. 75. CENTRIFUGAL BLOWER CONNECTED TO 15 H.P. DE LAVAL TURBINE.

is used in these wheels, as impact is not deleterious. Straight radial blades appear to be as satisfactory as any. The wheels are set in volute cases, like those of centrifugal pumps, and are run at even higher speeds than they, but even at such speeds as 3,000 or even 4,000 revolutions per minute, high pressures are unattainable

with wheels of this type. Fig. 75 shows such a blower connected to a De Laval steam turbine.

If the central orifice of the blower be 1 foot in diameter, and the length of the blades 6 inches, we can work out the pressure attained as before; for the compression of the air is so slight that it does not appreciably affect its volume. In this case the maximum head with 3,000 revolutions is 2,715 feet of air, or 3 feet of water (1·35 lb. per square inch).

For pressures higher than 20 inches of water, it is advisable to use either a compound blower or else a reciprocating pump or bellows. The reciprocating pump is always open to the objection that, as the air is at rest in the cylinder, a very large cylinder or bellows is necessary to deal with any quantity of air; the more so that a certain amount of throttling in the admission valves is inevitable, so that at the beginning of the stroke the air is even below atmospheric pressure. For low pressures this defect puts the reciprocating air pump quite out of court, and it is advisable to use a high speed centrifugal blower, or else a fan of the screw propeller type.

We have already pointed out that the screw propeller is a reversed reaction wheel, and the common blower fan may also be considered as a reversed reaction wheel of the parallel flow type. This fan running singly is capable of acting only against very moderate pressures. It may, however, readily be compounded by the insertion of fixed blades between a series of fans. It is clear that the resulting blower is a reversed turbine of the compound reaction type, with parallel flow; is, in fact, a reversed Parsons turbine.

The builders of the Parsons turbine have naturally devoted attention to the construction of such blowers, and have attained very satisfactory results. The blower

has an enormous advantage over the reciprocating air pump or bellows, in the quantity of air with which it is able to deal. A pair of engines now under construction at Heaton works for the Consett Iron Company, are each capable of dealing with 21,000 cubic feet of air per minute, and delivering at a pressure of 15 pounds above that of the atmosphere.

It is clear that such quantities of air cannot be touched by reciprocating pumps, which seem likely to give place more and more to turbo-blowers. The limitation of these latter is the pressure which can be attained by their means.

We have already pointed out that any reaction turbine is reversible, so as to form an air compressor, and it follows that the Parsons turbine of the ordinary type would operate as a turbine blower. However, it is natural to suppose that the blades of a turbine blower should be more oblique to the flow of air than are those of a steam turbine. The ratio of compression is always small as compared with that of expansion in the steam turbine, and it is not, therefore, necessary to shorten the blades as the high pressure end is approached. The diminished volume of the air may be allowed for by diminishing the speed of its flow, as may clearly be done by increasing the obliquity of the blades.

The air passes through a stage of compression in each blade row, whether fixed or moving. The total compression is the product of the compressions in every row, and may be easily estimated.

The greatest difference of pressure that can possibly exist between the two sides of a moving blade row is that difference which could give to air, at rest on the high pressure side, a velocity along the blade greater than that of the blade itself in the same direction.

If the diameter of the drum be 2 feet, and its speed 3,000 revolutions per minute, then the blade speed is 314 feet per second. Now suppose that the blades are inclined at an angle of 30° to the direction of their motion (they must then be only slightly curved); the velocity of each blade in the direction of its own surface is (314 feet per second × cos 30° or) 258 feet per second. The maximum difference of pressure between the two sides of a blade row is, therefore, that capable of generating a velocity of 258 feet per second, and this corresponds to a compression of about 5 per cent. It can be seen very easily that the theorem applies both to fixed and to moving rows, so that fourteen rows in all, or seven fixed and seven moving rows, will be necessary to double the pressure.

It is, of course, required that there should be a flow against the back pressure, and therefore more than 7 moving rows will in fact be needed, and to compress a large volume of air to 15 pounds above the atmosphere, it would be desirable to have ten rows at least.

Provided the pressure against which the machine is working is less than that pressure for which it was designed, the flow of the air is stable. If, however, when this stable motion is established, the discharge of air be checked, the engine may continue to deliver air at a pressure raised very far above the limit, but the flow is no longer stable, and the air is apt to cough back through the blade rows, while the discharge pressure falls suddenly.

The Parsons turbo-blower is obviously suited for connection to a Parsons turbine running at the high speed for which the blower is adapted, and this combination is quite unequalled by any other compressing plant delivering air at pressures of 1 to 30 or even 40 pounds per

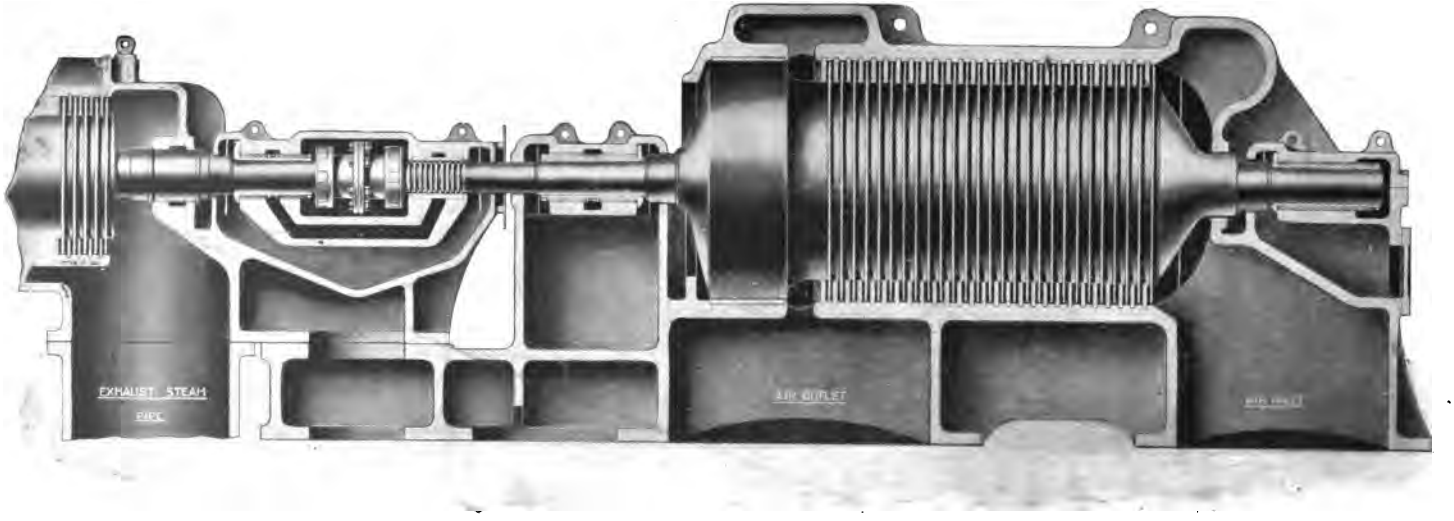


FIG. 76. PARSONS TURBO-BLOWER DIRECTLY CONNECTED WITH PARSONS STEAM TURBINE.

square inch. Pressures higher than these involve a multiplication of blade rows, which is somewhat undesirable, though a pressure of 75 lb. has been successfully obtained. If there were no alternative but the reciprocating pump, with the absurdly large cylinder necessary to collect air at atmospheric pressure, the blower would remain the most desirable compressor. It appears, however, that there is a more satisfactory alternative, consisting of a combination of blower and reciprocating pump. In such a combination the large low pressure cylinder of the force pump can be done away with, and the blower will deliver air to the high pressure cylinder at a pressure of about 30 pounds per square inch, and occupying only 40% of its volume at atmospheric pressure.

The continuity of the blast derived from a turbo-blower, and the high duty which it is possible to obtain from it on emergency, by a slight increase in the speed of the driving turbine, make it an engine of no mean merit in the present, and one likely to become more and more popular in the future.

CHAPTER X.

THE GOVERNING AND OPERATION OF THE STEAM TURBINE.

WE may divide steam turbines broadly into two classes, nozzle turbines and blade turbines, according to the formation of the passages through which admission takes place. These classes are not conterminous with those of impulse and reaction turbines. The Zoelly turbine, for instance, which is purely an impulse machine, has blade admission, whereas admission to the Rateau turbine, where there may be some reaction, is by nozzles.

Whatever the class to which the engine belongs, it is necessary at times to run it at a power less than that for which it was designed, and it is a question of considerable importance how this may be done with the least disturbance of the internal conditions and the smallest loss of thermodynamic efficiency. In the early days of the reciprocating engine, reduction of power or speed was effected, as now on some few engines, by a throttle valve in the main steam pipe. Of course this throttling reduced the pressure of the steam at admission to the cylinder, and so occasioned a loss of energy by no means inconsiderable. The introduction of Stephenson's link was a step in the right direction. By "notching up" the cut off was accelerated and the period of admission of steam into the cylinder reduced; notching up, how-

ever, occasioned a dead loss, by throttling the flow into the cylinder at the period of complete admission. This disadvantage was in turn abolished by the introduction of the Corliss valve with its instantaneous cut off, and a great increase in the economy of regulation was the result. When control is effected by this means the cut off takes place earlier in the stroke while there is little steam in the cylinder, and a more complete expansion is obtained.

It might be expected that, allowance being made for the resistance of the engine itself, this complete expansion would raise the efficiency of the engine at half load; but, as a matter of fact, great expansion in a single cylinder is not an unmixed benefit, for the temperature of the steam falls with expansion, evaporation takes place from the cylinder walls, so that these are cooled, and cooling and condensation of the live steam at the next admission are the highly undesirable results. It is for the purpose of avoiding losses from these causes that modern high pressure engines are designed to permit the expansion of steam in a succession of cylinders; but even in a triple expansion engine there is considerable variation in the temperature of the cylinder walls, and the losses from this cause are still the most serious item in the waste heat account, even when running at full load.

Now, in a turbine running at full load, there is no variation in the pressure or temperature of the steam which comes in contact with any given blade row, and consequently the most serious cause of loss is wanting. For this reason alone it may be fairly anticipated that the steam turbine will, when its construction has become the subject of further experience, far surpass the reciprocating engine in efficiency of working.

The question before us now is this:—How far is it

possible to maintain this advantage of the turbine when running at low load or at low speed?

If we consider first of all a nozzle turbine, such as the De Laval or the Curtis, the answer is a simple one. When running at full load the blades are in contact with the steam during only a portion of their revolution. If there be an almost complete vacuum in the turbine case, as in the De Laval turbine, the loss of heat in the buckets during their idle motion is trifling, and, when they come next into contact with the steam, a free passage is afforded for it. In the De Laval turbine, and in the Curtis where the nozzle expansion is incomplete and where the steam pressure in the first row of moving buckets is consequently higher than in the wheel case, it is found advantageous to group the nozzles together so that the pressure in the wheel passages may be maintained throughout their period of service.

Except as above mentioned, the action of the steam escaping from each of the nozzles in all the turbines of this type is entirely independent, and, therefore, no loss of efficiency will be occasioned by closing one of the nozzles and leaving the others in operation. This regulation by nozzles is the means adopted in all these machines. The early patents of Curtis describe a system of regulation by narrowing the neck of each nozzle, but this has been abandoned in favour of the obviously better practice of closing the nozzles successively from one end of the row. When one of the nozzles is partially closed there is a slight loss of efficiency owing to the "wire drawing," of the steam passing through it, but as the efficiency of action of all the rest of the steam is not affected, this may be regarded as negligible.

It has been suggested that some advantage might be gained by extending the regulation to the nozzles of the

second and third stages in order to avoid undue drop in pressure in the stage chambers, but we are not aware that this has been tried in practice.

The regulation of blade turbines is a problem much more difficult of solution. The elementary and obvious means is a throttle, but the limitations of that system have already been explained. It is, however, used in some turbines, and it has the advantage of maintaining a continuous flow of steam and a constant temperature in every part of the engine when running at low load. The relay valve throttling device used by Escher Wyss and Company not only on the Zoelly turbine, but, with certain modifications, on their water turbines also, deserves mention.

The operative part of this mechanism is a floating lever attached at one end to the governor, by which it is raised or lowered; at the other end the fulcrum of the lever is formed by the end of a rod carrying both the valve itself and a piston operating in a steam cylinder. At a point on the lever is attached a spindle carrying the slide valve, which controls the steam in the piston box. The immediate effect of raising the lever is the raising of the slide valve and consequent depression of the piston and closing of the throttle. This action is prompt and vigorous. But, as the throttle closes, the slide valve descends, with the fulcrum of the lever, and the throttle comes gradually to rest *before* the speed has fallen to the normal. Lastly, as the speed falls and the governor returns to the normal position, the slide valve is depressed below the normal, and the throttle is gradually opened again until the position of equilibrium is reached. The combined power and delicacy of this governor render it an exceedingly pretty and valuable mechanism.

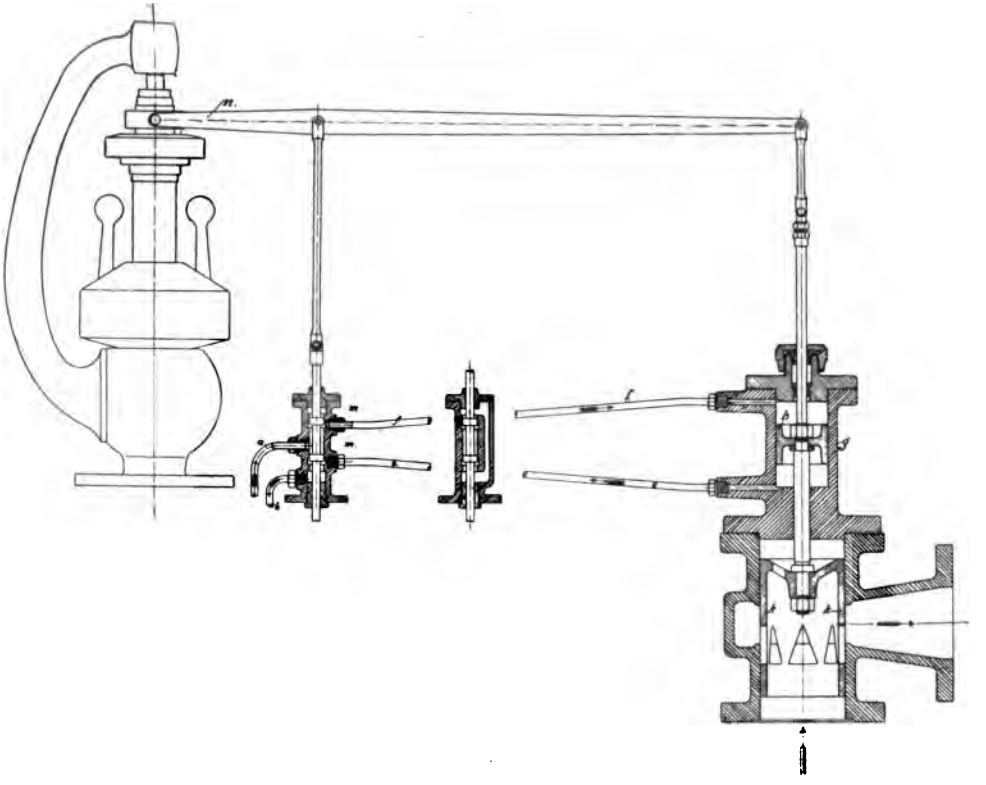


FIG. 77. RELAY GOVERNOR FOR ZOELLY TURBINE. (ESCHER WYSS AND CO.)

The simple throttle valve was not thought sufficiently economical for the Parsons turbine, and the mechanism previously described (p. 144) was adopted in consequence. This governor deserves a somewhat fuller consideration than has yet been accorded to it. The essential feature of difference from the Zoelly governor is in the fulcrum of the floating lever, which in the Parsons turbine has a periodic oscillation. There is a certain purely mechanical advantage to the governor in this oscillation, for the following reasons.

The essential virtues in a governor are that it should be (1) Prompt, (2) Powerful, and (3) Sensitive. In the Parsons governor the adjustment of the position of the throttle takes place two or three times in every second, so that the action of the governor is exceedingly rapid. Further, since the moving pressure on the throttle is that of boiler steam, its power is hardly open to criticism. But the rare virtue of this particular governor is its exceeding sensibility.

The use of relay governors (in which the power actuating the valve is derived not directly from the governor but from some other source controlled by it) is now common. Such a governor is that of Zoelly. But the Parsons is a double relay governor; for the steam moving the throttle is controlled by the slide valve, and the slide valve is moved by the rocking lever, and only the fulcrum of this lever is adjusted by the governor. It is possible to construct an exceedingly delicate governor on these lines, for it is not limited by the condition that it must be strong enough to overcome frictional resistances and set the link work in motion. The motion is already there, supplied by the cam, and the governor has no friction to contend with, but will answer to the slightest deviation from the desired speed by affecting the duration of the steam blast.

The mechanical perfection of this governor can only be attained by the use of intermittent admission, and some further consideration is due to the thermodynamical effect of this action. Now it must be admitted that, in running a turbine at half load under this system, we lose to some extent the advantage of continuous action, which maintains the temperature of the high pressure end of the turbine. We lose this, however, to a very small extent only, for, although when the throttle is shut steam in the high pressure stages expands and cools, yet the capacity of these stages is so small that they are almost immediately emptied of steam, and the cooling of the blades and consequent condensation of steam (if any such results) at the next admission, are negligible, when compared with that which takes place even in a high speed reciprocating engine.

It appears, then, that the Parsons governor is one of rare merit, and performs its task in a very satisfactory way. At the same time it must be admitted that this task, the regulation of a blade turbine for variations of load at a constant speed, is more difficult than that of regulating a nozzle turbine for the same conditions, and does not admit of quite so satisfactory a solution.

If on the other hand we consider the case for and against the nozzle turbine on the issue of regulation for varying speed, our judgement must be in favour of the blade type, or rather in favour of the reaction turbine with blade admission, of which the only examples are the Parsons turbine and the Schultz turbine as constructed for stationary use (in the Schultz marine turbine, according to Stodola, the action is in the high pressure stages impulsive). The blade speeds in the impulse turbines do not appreciably affect the flow of steam, and if such a turbine be slowed down by overloading, there will be

some increase in torque, but no diminution in the steam consumption. Our consideration of the De Laval turbine showed us that, in an impulse turbine (particularly if the pressure stages be few), the full blade velocity is essential for efficient working, and the effect of reducing the speed is consequently a loss of efficiency more or less serious.

In the Parsons turbine, on the other hand, the blade speeds are never so great as, on theoretical grounds, might seem proper; but this is not a matter of so much importance in a reaction machine, and a still further reduction of the speed does not seriously impair the economy of the action. If the speed of a Parsons turbine be reduced by overloading, the steam consumption is automatically reduced by the greater resistance inside the cylinder, and the torque is somewhat increased, the low pressure rings bearing the increased pressure. A comparatively small adjustment of the throttle valve or of the governor will therefore cause a considerable reduction in speed, and that without any great loss of efficiency, and this fact has greatly contributed to its success at sea. It may be noted that a reduction of the speed of a set of marine turbines will increase the proportion of work done in the low pressure cylinders, just as the same effect is produced in a compound engine by shortening the low pressure cut off.

A suggestion has been made that some advantage might be taken of this fact in vessels, such as the Cunard greyhounds, in which the high pressure turbines drive the outer shafts, by running at half speed with one high and one low pressure turbine under steam, exhausting from the high pressure cylinder on one side to the low pressure on the other. It is contended that the excessive load on the low pressure drum, which is the nearer to the keelson, would operate to keep the helm steady, and any deviation

from this condition could be compensated by the admission of boiler steam, through a reducing valve, to the low pressure cylinder.

It is clear that no sensitive governor is required on the marine turbine; small variations in the propeller speed are of no consequence, and throttling is obviously preferable to gust admission where there are two turbine cylinders and a considerable volume of steam in the connecting pipe. To prevent racing in a seaway, all marine turbines are fitted with a runaway governor, which operates powerfully as soon as the speed has increased beyond a definite limit from five to ten per cent. higher than the normal full speed. Owing, however, to the depth of the propellers of turbine vessels below the surface and to their small diameter they have never yet been known to race, so that no case of operation of the governors is at present on record.

* * * * *

A word must be said about the conditions of running which are desirable in a turbine installation.

We have already pointed out that a very high vacuum is valuable, and have drawn the inference that the condenser should be placed in immediate proximity to the exhaust. This is usually effected by placing the condenser beneath the floor of the engine room, so that steam passes into it almost without the intervention of a pipe. Such pipe as there is must be very large. A horse and cart could pass down the exhaust pipes of the Cunarders under construction, without inconvenience.

Another point to be considered is the desirability of superheat. It is well known that, when saturated steam is expanded, some of it is immediately condensed, and if saturated steam undergoes the large expansion which takes place in a turbine cylinder the condensation is

bound to be considerable. Now not only is the condensed steam incapable of further expansion and therefore of doing work, but it adds seriously to the friction on the blades, and so delays the flow and tends to wear the blades away.

By sufficiently superheating the steam after it leaves the boiler, this condensation can be got rid of, and the amount of superheat necessary for the purpose depends on the ratio of expansion. Consider for a moment the condition of the steam used in the standard tests of Parsons and Curtis turbines referred to on pages 128 and 208. The steam pressure at admission is about 200 pounds, and the superheat 150° Fahr. The volume of the steam is then 2·72 cubic feet per pound, and it expands approximately according to the law, $P.V^{\frac{17}{16}} = \text{Constant}$. When the pressure has fallen to 1·4 pound absolute (a vacuum of 27 inches of mercury), the volume will be about 305 cubic feet per pound, and the temperature 115° Fahr. The steam is then saturated, and any further expansion will involve a partial condensation.

Now in the tests of the Parsons turbine, the expansion was carried slightly further, and a steam consumption of 15·4 pounds per kw.-hour was obtained. In some German tests of a Parsons turbine, where 225° Fahr. of superheat were used, with the same pressure, a steam consumption of 14·9 pounds was obtained.

Turning to the Curtis test, we find a vacuum of $28\frac{1}{2}$ inches employed in the condenser. The pressure in the last nozzles must have been lower still, for the friction on the blades in the last chamber would cause a certain rise in pressure as the steam passed through the blade rows.

It follows that considerable condensation must have

taken place in these nozzles. Now when steam passes through expanding nozzles the speed of the whole increases until condensation begins; but so soon as any of the steam is condensed the acceleration of that portion stops; for the water drops, though infinitesimal, are yet far more heavy than the molecules of steam, and cannot be accelerated by the impact of these molecules. The acceleration of the remaining steam still goes on, and, by reason of the latent heat of the steam condensed, the remainder attains a velocity higher than that due to its mere expansion; so that, when discharge takes place, there is a certain amount of steam moving with very high speed, and a straggling tail of infinitesimal water drops, moving with all manner of smaller velocities, from about 2,000 feet per second upwards.

It is clear that these water drops will actually exert a back pressure on the last blade row, as the first two rows deprive them of their whole velocity, and their deleterious effect upon the economy of the machine is great. We may therefore infer that the Curtis turbine stands to gain even more than the Parsons from increased superheat, and the De Laval will benefit in almost the same degree.

This suggestion is borne out by the benefit experienced from moderate superheats in connection with the Curtis turbine, and there can be little doubt but that, if the superheat of 225° Fahr. can be applied to the Curtis turbine without injury to the first blade row, a very high efficiency will result.

CHAPTER XI.

THE FUTURE OF THE STEAM TURBINE.

THE rapidity with which the turbo-generator has been taken up of late years by the most progressive and successful engineers lends a certain interest to speculation as to the probable future of the engine. The present demand for steam turbines makes it seem likely at first sight that they will before long entirely displace the reciprocating engine from all large undertakings. Whether this belief is justified can only be shown by the event, but some consideration may be given to the relative merits of the turbine and the reciprocating engine as prime movers.

The only steam turbines which have as yet been manufactured on any large scale, are those of Parsons and Curtis, and no large units of any other type have shown an efficiency comparable with that of these machines. The largest Parsons turbines built by the inventor are the 4,000 kw. machines running at the Carville power station on Tyneside. Larger turbo-generators have, however, been constructed by Messrs. Brown, Boveri and Co. of Baden, under licence from Mr. Parsons; and the turbines now building at the Wallsend Slipway for the new Cunarder, will develop about 17,500 H.P. in each turbine cylinder, or 35,000 H.P. in each complete turbine, consisting of the high and low pressure parts. The largest

Curtis turbines at present constructed are the 5,000 kw. machines running at Chicago. Their steam consumption is 15·8 pounds per kw.-hour, as against 15·4 pounds, the lowest consumption obtained with the Carville turbines, and 14·9 pounds the corresponding figure for the Parsons turbine of Messrs. Brown, Boveri and Co. In the case of smaller units the low steam consumption is not quite maintained by turbines of any type, but the small machines of De Laval are unsurpassed.

In choosing between the various prime movers available for stationary work, the engineer must look to their economy in, among others, the following relations:—

(1.) First cost.
(2.) Cost of station and erecting.
(3.) Wear and upkeep.
(4.) Coal and oil consumption.
(5.) Attention required.

(1.) Now as to the first cost, we have seen that large turbine units of the Parsons type can be built at considerably lower cost than triple expansion engines of the same size. There is little to choose between the two when units of 1,000 to 2,000 kw. are concerned, and in the case of smaller units the advantage is rather on the side of the reciprocating engine. When we get below 1,000 kw., too, another competitor comes into the field, in the form of the internal combustion engine, using producer gas. This last seems to be very much more economical than the steam engine, as may reasonably be expected from the abolition of that most exorbitant middleman, the boiler, but it is handicapped by the unsuitability of internal combustion for large engines, and by the deleterious effects of the high temperature inside the cylinder.

The cost of the Curtis turbine appears to follow much the same law. Some of the German engines have been

more cheaply produced, but they pay for the saving in coal.

(2.) When we come to the cost of erecting, housing, etc., the advantage is entirely on the side of the turbine. There is, in the first place, an immense saving of space by their adoption, and a consequent reduction in the size and cost of the engine house, attended by the advantage that the engines are very much more under the eye of the engineer in charge. The economy of the Curtis turbine from this point of view is even more striking than that of any other.

But every form of turbine has another conspicuous advantage in the absence of vibration attending its motion. A reciprocating engine (and gas engines are the worst sinners of all in this respect) requires very heavy foundations and massive bedplates, which must be laid down at considerable expense. The weight of piston, piston-rod, connecting rod and other reciprocating gear moving to and fro at the high speeds required for the driving of dynamos, coupled with the thumping of steam admitted alternately to the opposite ends of the cylinders, causes a noise and vibration perceptible, not only in the power house, but too often throughout the neighbourhood; a vibration which not infrequently exposes the supply company to the risk of indictment for nuisance, or to an action for heavy damages consequent on injury to the foundations of neighbouring buildings. It will be interesting to see whether the attitude of the courts towards reciprocating nuisances is at all affected by the possibility of running a big station quietly, where turbines are installed.

(3.) The Parsons turbine, as we have already pointed out, has only two bearings under stress, the Curtis turbine has only one, and in each case high pressure lubri-

cation is used, the Curtis rotor being completely oil borne. The stresses on the bearings, too, are due only to the weight of the moving parts, and are both smaller and simpler than those on the bearings of a crank shaft, while the wear is uniform all round the journals, a condition not obtaining in the reciprocating engine. Lastly it may be noted that the turbine contains no high speed or hot wearing surfaces like the cylinder walls, and there is no packing or stuffing anywhere in the steam turbine.

On the other hand, the wear on the blades must be considered. The Curtis turbine has been on the market for so short a time that it is difficult to speak definitely of the erosion and corrosion of its buckets. It is maintained by the makers that there is very little of either, and that the life of the blades, when superheated steam is used, is practically indefinite. At the same the steam velocities in the Curtis turbine are very much higher than in the Parsons, and the pressure of the steam on the buckets is greater, so that it seems reasonable to suppose that the English machine will be the more durable. We are not aware that any destruction of the blades has been experienced on the Parsons turbines that have now been running in this country for periods of nearly twenty years.

When we bear in mind the continual trouble that is experienced with glands and packing rings in the reciprocating engine and the great loss of efficiency which results from wear on the slide valve surfaces, causing leakage of steam and water, we must concede that the steam turbine promises to be a very much more durable and less troublesome machine.

(4.) The steam consumption of the two types of steam turbine under discussion has already been considered.

We have seen that the large Parsons turbine units compare very favourably in this respect with the triple expansion engine, and vastly surpass the best recorded performances of the compound. It is a further merit of the turbine that its efficiency does not diminish with increasing age, and that a high boiler pressure is not essential to efficiency provided that the vacuum is a good one. Taking into account the fact that steam turbines are very commonly run under a lower boiler pressure than that adopted for reciprocating engines (a fact particularly noticeable in the published comparisons of marine engines) the advantage of the steam turbine in point of coal consumption is generally rather more than appears from the comparison of feed water or steam per H.P. hour. And it must also be remembered that the reciprocating steam engine is now a highly perfect mechanism, and has probably touched its limit of efficiency, whereas every type of steam turbine is still in comparative infancy, and their steam consumption is reduced every year.

It is clear that the greater expansion of the steam possible in a turbine furnishes it with a greater supply of energy per pound of steam than is available to the reciprocating engine. It lies with the designer so to modify the modern turbine forms as to reap the full benefit of this additional energy. Thus the turbine has possibilities of efficiency which do not exist for the reciprocating engine.

Further, the most fruitful source of loss in the old engine, the alternate cooling and heating of the cylinder walls, is absent in the turbine; and the greater mechanical simplicity of the turbine is immediately apparent. On every ground, then, we may fairly anticipate that the turbine will, within the next few years, so completely excel the reciprocating engine in the economy of its working,

that the most conservative engineer must perforce declare himself a convert to the new prime mover.

High pressure lubrication, with return of the oil, through a filter, to the pump once more, is now the prevailing system on engines of every type. A certain proportion of the oil is lost in each cycle, depending on the number of bearings supplied and on the speeds and stresses in each bearing. The bearing speeds in a turbine are rather greater than in the competing engines; on the other hand the number of bearings is less. It is a vexed question whether or no the Parsons turbine consumes less oil than the reciprocating engine. The examples of the latter cited in the discussion are of course the best that can be found, but on the whole the supporters of the turbine seem to have rather the best of it.[1]

(5.) Lastly, when we come to compare the attendance required by the turbine with that necessary for the reciprocating engine, the advantage is all on the side of the former, and this for two reasons. In the first place the smaller number of parts—the rotor is the only moving part of any size, or subject to stress of any magnitude—saves almost all surveillance and lubrication, and makes it very unlikely that anything should go wrong; and, secondly, the compactness of the machine, and the small space occupied by it, makes it easy to keep an eye on several units at the same time, and to move quickly from one to the other. It may be added that the introduction of the steam turbine into a factory considerably diminishes the risk to operatives of injury by the machinery, as the impossibility of getting entangled in or crushed by a steam turbine may readily be conceived.

It appears, then, that in a comparison between the turbine and the reciprocating engine as a stationary

[1] Discussion at the Institute of Civil Engineers.

source of power the old-fashioned engine comes off a very poor second.

If, however, we turn our attention to the adaptability of the two machines for vehicular propulsion, we shall be compelled to take a different view.

Every steam turbine, if it is to work economically, must exhaust into a condenser, and a condenser is equally impossible on a locomotive engine and on a motor car. In addition to this, the flexible shaft of the De Laval turbine, and the large wheels and small clearances of the compound impulse turbines unfit them for running in bearings subject to violent jolting. The Parsons turbine, which is more solid in construction, is put out of court by the large steam consumption of the smaller machines, particularly when non-condensing, and by the small starting torque which they are capable of exerting, for if steam be blown through the cylinder of a Parsons turbine with the rotor at rest the resulting torque is not very much greater than that which would be exerted at full speed. Thus it is not possible to exert a large torque when required, by slowing the engine; so that, both for hill climbing and for starting, the Parsons turbine would be entirely unsuitable.

When, on the other hand, we consider the problem of marine propulsion, the advantages of the Parsons turbine appear unique and of the last importance. Here the saving of space effected by the turbine is of great value, and the engine appears to be peculiarly adapted for the economic use of steam for purposes of propulsion.

There can be no question as to the advantage of an engine room free from links and frames up to the level of the upper deck, and occupied only by the turbine cylinders on the floor. The compactness of these contributes greatly to the safety of the engineers and greasers,

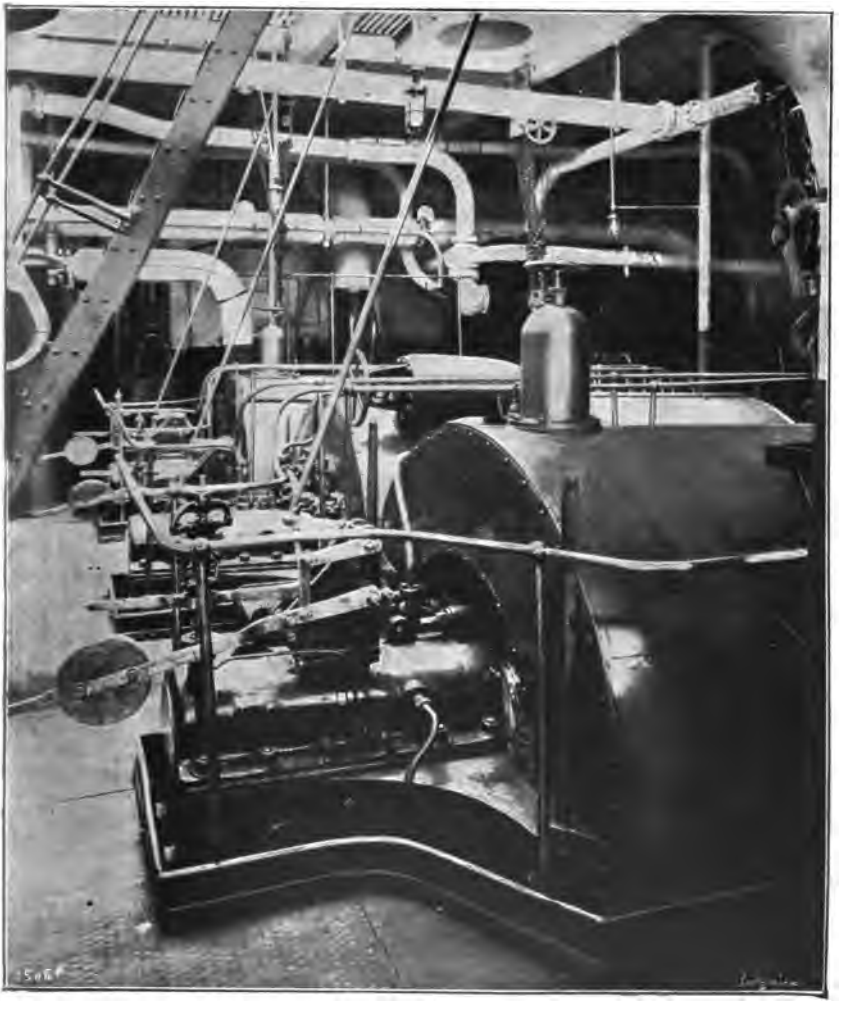


FIG. 78. TURBINE ROOM OF SS. "LONDONDERRY." (REPRODUCED FROM "ENGINEERING.")

and reduces the necessary staff to a certain extent. The lower boiler pressure also diminishes the discomfort of the stokehold.

The engine room itself may be smaller when turbines are employed, and the hull need not be so heavily strengthened in the region of the bed-plates, on account of the absence of vibration and the stresses inevitable where the reciprocating engine is employed.

But perhaps the most important advantage of the turbine in a passenger vessel, is the increased comfort of passengers, particularly at night and in berths near to

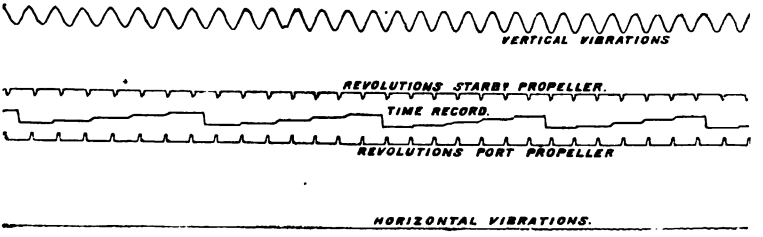


FIG. 79. VIBRATIONS OF HULL OF SS. "CARONIA" (QUADRUPLE ENGINES).

the engine room, from the absence of the continuous thumping which makes sleep impossible to the most experienced traveller during the first night at sea. In the modern turbine vessels, the smoothness of running is so marvellous, that the author has been unable to discover, from the sound or vibration in the cabin of a channel steamer, whether the engines were running or not at any particular moment, and even the delicate seismograph employed on the *Carmania* during her trial trip scarcely detected the slight vibrations which appear on the record (Fig. 80).

A point of the utmost importance in marine architecture is the allowance of a sufficient metacentric height to

ensure great stability in a short roll. Both for comfort and safety it is desirable to have a low centre of gravity of the vessel and engines, since these cannot shift, while the cargo can. The heavy cylinders of a reciprocating engine, on a level with the main deck, are, therefore, an unmitigated evil, and the increase of stability arising from the use of turbines is among their many advantages.

A gain of even more importance arises in connection with the use of steam turbines for the propulsion of war-ships from the fact that the turbine is entirely below the water-line and so protected from the enemy's shells. In addition to this, the turbine itself is by no means an easy

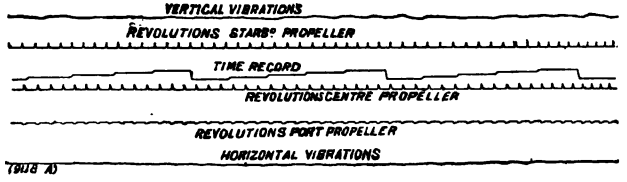


FIG. 80. VIBRATIONS OF HULL OF SS. "CARMANIA" (TURBINES).

machine to injure; nothing but the direct impact of a shell on the turbine case could do serious damage, and the target presented is very small in comparison with the vital part of a ship propelled by the old method.

In armoured vessels, as is well known, the armour deck springs from the belt and arches over the engines, so that, while the deck must be raised to a considerable height, adding to the weight of the vessel and diminishing its stability, the connecting rods must also be shortened, to the detriment of the engine's efficiency. These engines are, therefore, less fitted than those of other vessels to contest the pre-eminence of the turbine, and it is fair to suppose that the trials of the *Dreadnought* will clearly establish the magnitude of the gain which is to be ex-

pected from the adoption of the steam turbine in this branch of the service.

Engineers have recognized that the steam turbine is the engine of the future, and the increasing output of the various turbine works affords ample evidence of the fact. The total power of the Curtis turbines now built, or under construction, is 800,000 horse, and the same figure has been reached by the marine steam turbines constructed under the Parsons patents. The Parsons turbo-generators now running are even more numerous, and attain a total horse-power higher still.

CHAPTER XII.

ON THE TREND OF MODERN SCIENTIFIC INVENTION.

THE spirit of the age, whose high priest in days gone by was Matthew Arnold, has spread his cult of late years throughout society, and is recognized as having a somewhat peculiar dominion over the spheres of literature and art.

The influence of this power in the more sordid realms of science and engineering is a fact which has hardly yet been appreciated, but a fact none the less; and this influence has never been so great as at the present day, when the gap between the engineer and other members of the educated public is being bridged, at once by the university training of the engineer (a development of the last few years) on the one side, and, on the other, by the wide public interest in the problems and progress of engineering science. The department of engineering enterprise which touches most frequently and intimately the general public is that which bears upon traffic and locomotion. Partly as a result of this fact, the invention of the petrol engine and consequent introduction of the automobile and the motor omnibus has aroused of late years a greater interest in science than has ever been experienced since the days of Hudson the railway king.

There can be no doubt that the invention of the steam turbine has contributed in no small measure to this effect,

but the present change in the form of the steam engine is a less striking manifestation of the spirit of the age than is the supersession of the steam engine itself as a motor for the development of small powers. This change is particularly obvious in the department of traction. Here the steam engine has always suffered to a certain extent from the impossibility of getting a starting torque very much larger than that which is exercised when the engine is running at full speed. The petrol and the oil motor are even less satisfactory in this respect. The difficulty has been overcome so far as road cars are concerned by the now familiar device of changing gears, but this is applicable only to the lighter vehicles, and is out of the question for railway engines and the like. For this reason it appears inevitable that the electric motor will ultimately displace those of every other form from those railways on which frequent stops are the prevailing rule.

The growing use of electric power, while diminishing the employment of small steam engines, increases very greatly the demand for those of high power for the purpose of driving the electric generators, and it is notable, as an instance of the far-reaching power of this Zeit-Geist of which we have been speaking, that it is precisely in the high power machines that the superiority of the turbine over the reciprocating engine becomes most obvious and undeniable. On the other hand the internal combustion engine, burning oil, gas, or petrol, which is superseding the small steam engine, does not require the existence of steam power in the background.

An obvious advantage of the internal combustion engine over that using steam is the decrease in weight and bulk consequent upon the abolition of the boiler, but it is an important fact that the proportion of fuel used per horse-power-hour can be reduced to a much lower figure

in the oil engine than in one in which steam is the acting fluid. This is particularly conspicuous in the case of the Diesel motor, which works without explosion, by the steady combustion of oil vapour within the cylinder.

Now if the turbine is better than the reciprocating engine, and the oil engine superior (letting alone the limitations introduced by heating) to one using steam, it would appear that an internal combustion turbine would be the best engine of the four.

It is scarcely necessary to say that innumerable attempts have been made to produce such an engine, but without success. The archives of the Patent Office are full of the dreary records of disappointed hopes. In spite, however, of the despondency of most engineers on this point, it seems probable that in the course of a few years some method of dealing with the difficulties presented will be found. But before we turn our attention to the practical problem involved, there is one preliminary objection demanding a certain notice.

It has been urged that the steam turbine rivals in efficiency the reciprocating engine only by reason of the greater expansion possible in the turbine cylinder, and the inference is drawn that, as the exhaust gases of an internal combustion engine are incapable of condensation, so an internal combustion turbine would necessarily be inferior in efficiency to a reciprocating engine of the same type. It is sometimes forgotten by the supporters of this view that the internal combustion engine exhausts at a pressure very much above that of the atmosphere, and that nothing like complete expansion takes place in the cylinder. If then a turbine of this type were produced, it would maintain an advantage of precisely the same sort as that possessed by the steam turbine, and would probably show a very high efficiency.

There are two obvious systems on which an internal combustion turbine might be worked, corresponding to those of Diesel and Daimler in reciprocating engine practice. According to the first, which would seem on many grounds to be the preferable one, a combustion chamber would be formed in communication with the admission port to the turbine cylinder, and into this chamber air would be compressed. Gas or oil injected to this chamber would supply the heat required for expansion. On the other system, air, charged, by passing through a carburetter, with the vapour of petrol or of some other combustible spirit, would be admitted at high pressure to a combustion chamber and there exploded by an action either continuous or intermittent. Non-return valves would prevent lighting back.

The fundamental objection to both these systems, which have occurred to many inventors of turbines, is the high temperature of the gases admitted to the turbine cylinder, a temperature which is fatal to the edges of the blades, past which the gas flows with great speed and considerable friction. It has been found impossible, with the materials at present available, to construct turbine blades capable of resisting corrosion for the shortest times. This problem is, therefore, at present one for the metallurgist, and it is possible that some of the new steels now the subject of experiment may provide the desired solution. At the same time there are a number of questions of blade-design presented by steam turbines of every class, and worthy of the attention of the mathematician. It cannot be too strongly urged that the invention of turbines has opened a new territory, and offers a huge field for scientific investigation.

There can be no doubt but that engineers have shown of late years some appreciation of this fact, and both

professional men and amateurs have devoted a considerable amount of thought to the subject. The file of patents bears eloquent testimony to their not always well-directed application, and the waste of money and time which takes place annually in the pursuit of patents for inventions, either based on fallacies or unworkable by reason of difficulties unforeseen by the untrained technician, is matter for great regret. It is still more unfortunate that many inventions of real merit remain unprofitable and undisclosed on account of the dread experienced by the inventor (particularly if a man of small means) of the expense entailed, before a patent can be obtained and the necessary experiments carried out for proving the merit of the invention.

It may come not amiss if we devote a few words to the subject of patents in their practical bearing upon invention.

In all the more important states of the civilized world protection is granted to the inventor of new machines and the like, upon the condition that he file a complete description of the machine, which shall be available to the public, for the purpose of enabling other persons to carry out the invention after the expiry of the patent. To guard the inventor against the danger of publication during the experiments which may be necessary, and to enable him to describe fully the method of carrying his invention into effect, a period of six months is allowed before the complete specification need be filed, during which period provisional protection is granted to the inventor.

For the further relief and encouragement of inventors, the principal states have entered into a union for the protection of industrial property, and an application for provisional protection made in any country of the union

secures protection in all for the period of six months. This application must, of course, be accompanied by a description sufficient to identify the invention, but the description is not published until the complete specification is received.

The cost of obtaining, by the aid of a reputable patent agent, letters patent or the corresponding protection for a simple invention in every State of the Union may be roughly estimated at about £200, though, of course, it varies very much. It cannot be too strongly urged upon the inventor that to seek this protection without the assistance of a patent agent is at least as foolish a proceeding as to go into a court of law without the help of a solicitor, and it should be remembered that as much or more technical skill is required for the drafting of a complete specification as for that of a freehold conveyance.

The cost of obtaining letters patent need not, however, fall upon the inventor. So soon as provisional protection has been obtained, he will generally find it advisable to put his invention into the hands of one of the leading firms manufacturing the class of machine concerned. Such a firm is able to call upon wider experience in this class of work than can be possessed by any individual, and has at hand facilities for experiment greater than are likely to be at his disposal. It is usually worth while to make such communication in confidence, so as to avoid publication of the invention, in case misdescription in the provisional specification should necessitate the abandonment of the application and the taking out of a new patent.

Having regard to the possibility of this event, it is a commendable course to have the provisional as well as the complete specification drawn by an agent. It is com-

monly supposed that the drawing of a provisional specification requires no particular skill; and this is very frequently the case. But it happens lamentably often that a search in the file of patents, after provisional protection has been obtained, reveals the fact that the greater part of the invention has been anticipated; and the one element remaining on which a good claim could be founded, will generally be found to be the one not mentioned in the provisional specification, and, therefore, frequently incapable of being claimed in the complete.

In spite of these difficulties, however, the present patent law works with exceeding fairness both to the public and to the patentee, and great praise is due to the just and equitable practice of the Patent Office and of its present Comptroller, whose policy it has always been to show the inventor that encouragement which he of all men best deserves.

It is a fact, more and more appreciated of the public, that the inventor is its most valuable servant, since his work contributes not only to his own advancement but to the growth of industry, the employment of the people, the advancement of science, and the raising of the standard of life The inventor is hailed to-day as the herald of the millennium—a millennium, it is true, "of luxury and the electric button,"—but a millennium none the less, and one which it is the tendency of the present age to estimate at too high, rather than at too low a value—a millennium not without attractions even to the stoic.

We have hoped, in laying shortly before the reader some of the problems which are confronting the engineer of the present day, to contribute in some small degree to the realization of this ideal, and in that hope we close these pages until it shall please the public to reopen them.

APPENDICES.

APPENDIX I.

SOME MATHEMATICAL PRINCIPLES.

THE principles of mathematics involved in the elementary branches of engineering may be briefly summed up in one geometrical and a few mechanical propositions. The geometrical proposition is this:—

If a body has at the same time two velocities which may be represented by the lines AB and BC, then the line AC represents its whole velocity. And this is clear enough. If a man were to walk in one second between the points A and B on the deck of a steamer, while the vessel itself moved so as to carry the point that was at B into the position C, then the man would have the two velocities represented by AB and BC, and would move actually from A to C in the course of the second; so that his total velocity is represented by AC.

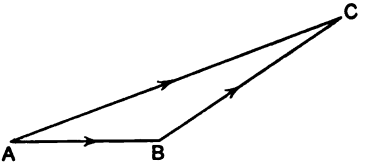


FIG. 81. DIAGRAM OF VELOCITIES.

Suppose that water flowed down a turbine blade in the direction AB, while the blade itself moved in the direction BC, and suppose that these lines are proportional in length to the corresponding velocities; then the whole velocity of the water is represented by AC, and it is quite clear that the relative magnitudes of the three velocities represented by these three straight lines depend on the angles of the triangle ABC, that is to say, on the angle at which the fluid is admitted to the turbine wheel, and on the obliquity of the blades.

Since the velocity represented by AC is made up of the velocities AB and BC, it is clear that, if a body change its velocity from AB to AC, then the change is the velocity BC, and, even if only the direction of the velocity is changed, that is, if AB and AC are of the same length, still there is a change of velocity which may be represented by BC. Now, if the body is moving round a curve, the direction of its velocity is always changing, whether its magnitude is changing or not, and the body is therefore constantly acquiring a new velocity, which we cannot represent graphically because the velocity acquired during any small period is itself small. This constant acquisition of velocity is called acceleration.

When the velocity of a body changes in direction only and not in magnitude, the acceleration is perpendicular to the direction of motion at any instant, for if it were in the direction of motion it would cause the body to move more quickly, and if it were in the contrary direction it would retard the body. The amount of the acceleration is, of course, proportional to the velocity, and to the rate of turning; so that, if a body is moving in a circle, it has a constant acceleration towards the centre proportional to the product of its speed of moving and its speed of turning; and this is equivalent to the square of the speed of moving divided by the radius of the circle.

MECHANICAL PRINCIPLES.

In the course of our discussion we shall use two laws, of which the one can, by the aid of the geometrical proposition already stated and a chain of mathematical reasoning, be derived from the other. For the sake of brevity we shall state these, the law of "conservation of energy," and the law of "conservation of momentum," as separate principles.

The latter principle may be stated as follows:—"No body or system of bodies can change its momentum, except under the influence of externally impressed force; and the rate of change is proportional to the force applied."

In this statement, which contains all the three laws of motion enunciated by Sir Isaac Newton, we have introduced a term requiring some explanation. The momentum of a body in any given direction, is the quantity of its motion in that direction, and is the product of its mass by its velocity. The momentum of a system of bodies is the sum of the momenta in the given direction, of all the bodies composing the system. Now the mass of a body does not ordinarily change—and here we touch on a third principle, that of conservation of matter—the rate of change of momentum is, therefore, the mass multiplied by the rate of change of velocity, in other words by the acceleration of the body.

If, then, a body is subject to acceleration, it must be under the influence of a force proportional to the acceleration and to the mass of the body, and for mathematical purposes force is measured by the "mass acceleration" which it can produce. Thus when a body moves uniformly in a circle it must be under the influence of a force towards the centre. It is a matter of common experience that it is necessary to apply such force by a guide, a string, or some other means, in order to secure the curvature of the path.

Now if one body be attached to, or press on, another, then the momentum of each will be changed by the force between them; but since there is no external force acting on the two bodies, the momentum of the system is not changed; so that whatever momentum is lost by one body is gained by the other. We infer from this that the force exerted by the first body on the second is equal and opposite to that exerted by the second on the first. This fact is enunciated by Newton as the third law of motion, "To every action there is an equal and opposite re-action."

If then a body moving in a circle is under the influence, as we know it to be, of a force towards the centre, it follows that it must exert on something a force away from the centre, and this phenomenon, which one may experience by swinging a weight on the end of a string, is that known to engineers by the term, somewhat unjustly condemned by mathematicians, of "centrifugal force," which is really the reaction of the body

against the means of constraint, and not a force acting on the moving body itself.

So far we have dealt only with the motion of small bodies or points, in discussing the motion of large bodies we must not forget their possible rotation; but it is necessary at this point to introduce a new term. The "angular momentum," about a given point, of a small body moving in a straight line is the product of its momentum by the perpendicular from the point on its line of motion. This quantity measures the amount of its "spin" about the point, and clearly it has no spin about a point on its line of motion.

When a large body is turning, the various parts of it are moving in all manner of different directions, with different speeds, and consequently with different momenta. The angular momentum of such a body about a point is the sum of the angular momenta about that point of all the constituent particles. To change angular momentum we must apply a turning couple, which consists, as the familiar process of turning a butterfly nut with finger and thumb indicates, of two equal and opposite forces acting at a distance apart.

By a little mathematical reasoning based on this fact (and as the reader can easily pursue the chain of argument for himself we shall not here enter upon it) we can deduce from the principle already laid down the further principle of the "conservation of angular momentum." This principle makes it clear that, if fluid enters a turbine wheel with angular momentum in one sense about the shaft, and leaves it with a less angular momentum, or with one in the opposite direction, then some turning couple must have been acting on the fluid in the wheel, and consequently an equal and opposite turning couple must have been exerted on the rotor by the fluid. The torque of the engine is, therefore, equal to the rate of change of angular momentum of the fluid in the wheel. This is the whole principle of the turbine, whether driven by water, steam, or any other fluid.[1]

[1] In the case of a large body rotating about an axis, the velocity of each particle is equal to the angular velocity of the whole, multiplied by the distance of that particle from the axis, and the perpendicular

The principle of "conservation of energy" is wider than that laid down in the foregoing pages, and may be briefly stated as follows:

"The energy of a body or system of bodies remains constant, unless work is done by or on the bodies, when it decreases or increases by the amount of the work done."

If we define energy, in what is probably the most satisfactory way, as capacity for doing work, we must furnish some further definition of the latter term in order to arrive at an understanding of the principle. Work is generally done when a moving body is acted on by a force, and the measure of the work is the product of the force by the distance moved through by the body in the direction of the force's action. Thus if a man lift a weight up by means of a pulley tackle, the work done by the man is the product of the force exerted by him and the length of rope passing through his hands. The work done on the body is the product of the weight of the body by the distance through which it rises; and, by the principle under discussion, these two quantities of work would be equal if there were no friction; for no energy resides in the pulley tackle, and that put in by the man is, therefore, equal to that given out to the load.

from the axis on to the line of motion of the particle is also equal to the distance of the particle from the axis. The angular momentum of each particle is equal to the product of the mass of the particle by its velocity and by that perpendicular, that is to say, to the product of the angular velocity of the whole body by the mass of the particle and by the square of its distance from the axis.

The angular momentum of the whole body is the sum of the angular momenta of all the particles, and is therefore equal to the product of the angular velocity by the sum of the products of the mass of each particle into the square of its distance from the axis. This last sum can be found by mathematical as well as by graphical methods. It is independent of the speed of rotation, and is in fact a constant of the body known as its "moment of inertia." The angular momentum of a turbine rotor about the axis is therefore the product of the "moment of inertia" by the angular velocity. (The angular velocity is 0·105 of the revolutions per minute.)

It is an important feature of angular momentum, and one capable of rigid proof, that it obeys the triangle law of superposition, with which we opened the discussion in this Appendix.

Classifying energy according to its phenomena and neglecting molecular activities and the like, we may divide the forms of energy into mechanical energy, on the one hand, and energy due to molecular arrangement, on the other. We shall further divide mechanical energy (postponing the consideration of the energy of gases) into potential and kinetic energy.

Potential energy is that possessed by a body by virtue of its position or strained condition. The energy stored in coal or gunpowder in a chemical form, or electrically in a Leyden jar, may also be classed as potential energy. Kinetic energy is that possessed by a body by virtue of its motion; and the two forms are mutually convertible without the intervention of external forces. An excellent contrast of the two forms of energy, as used in connection with water power, is furnished by the hydraulic jack and the Pelton wheel. We may notice the adaptability of each different form to produce the same effect, as shown in the propulsive power stored potentially in a bent bow, an explosive cartridge, compressed air, or a raised cricket bat; the propulsive power of a moving substance will not be called in question by any man who has ventured out top-hatted on a windy day.

Seeing, then, that a moving body has the power of doing work, let us see how the energy of a body of mass M moving with velocity V can be measured. Let us suppose that the body in question does work against a force P in moving through a distance S. Then the work done is clearly $P \times S$. Now if V′ be the velocity of the body after doing the work, and if T be the time occupied in moving through the distance S, then the distance is equal to the product of the mean velocity by the time, that is to say, $S = \frac{V + V'}{2} \times T$. The force, as we have seen before, is equal to the rate of change of the momentum, so that $P = \frac{V - V'}{T} \times M$, and the work done is therefore, $P \times S = \frac{1}{2}M(V^2 - V'^2)$. The difference between the energies of a body of mass M moving with velocity V and with the velocity V′ is therefore $\frac{1}{2}M(V^2 - V'^2)$; and it seems fair to assume that the energy in the first case is $\frac{1}{2}MV^2$. This is, in

fact, the kinetic energy of the body, and represents the amount of work which it is capable of doing.

If a body is at a height H above the ground, its potential energy is W × H where W is the weight. Its acceleration, if it be allowed to fall, adds in every second a velocity of a little over 32 feet per second. This acceleration, equal to 32·2, is known as G. Since the force of its weight produces an acceleration G, therefore $W = MG$. If it fall through the height H it loses its potential energy and acquires a velocity which we will call V. If the time of falling were T, then, since the mean velocity was $\frac{1}{2}V$, we have $H = \frac{1}{2}VT$, and since the acceleration was G, therefore $V = GT$. It follows that the loss of potential energy, that is to say, MGH, is equal to $M \times V/T \times \frac{1}{2}VT$, and that is equal to $\frac{1}{2}MV^2$, or the kinetic energy.

This is a simple and very important case of the "conservation of energy." We can infer from it that we ought to get exactly the same amount of work out of water in an elevated reservoir, whether the water drives an overshot wheel by its simple weight, or whether its potential energy is transmuted to kinetic, and it drives a Pelton wheel by means of a jet.

The Problem of Efficiency.

It appears from the foregoing that all the work that is put into a machine must come out again in some form or other. What then is meant by efficiency, if the machine cannot destroy the energy supplied? To answer that question we must consider the fact that energy exists in numerous forms, and that one of the commonest forms is heat. The energy supplied to the engine may be transmuted into heat and so given out in a form useless for practical purposes. The efficiency of an engine is the proportion of the energy supplied which is given out *in the desired form.*

The most fruitful causes of transmutation into heat are friction and shock, and if it be remembered that the 1,800

British Thermal units necessary to raise 1 gallon of water from freezing to boiling point are equivalent to ·707 HP.-hours of work (2545 B.T.U. = 1 H.P.-hour), it will be seen that a very little heating means a great loss of energy.

That friction converts energy into heat and so dissipates it is a fact within the experience of every one, but the deleterious effects of impact are less obvious. They may, however, be very simply demonstrated in the following way:

True shock takes place only between inelastic bodies, and, where there is shock, force is exerted between two bodies moving at different speeds. Now the rate of doing work is the product of the force exerted by the speed of motion in the direction of the force; and the force exerted by the working body is equal and opposite to that exerted on the other. Since, however, the velocity of the working body is necessarily greater than that of the body acted on, it follows that the first does more work than the second receives, and the balance is dissipated in the form of heat. It is therefore important that the action should not be one of shock, but should be a steady continuous one, even if it lasts for a microscopic time; and the reader will appreciate that it is this fact that makes the spring of a cricket bat, or of a golf club, a matter of the last importance. This, too, is the reason why the interposition of an elastic column of air (rendering the action smooth and continuous) has developed the spring gun into the very effective air rifle.

If it is required that a stream of water shall act on a turbine blade so as to press it forward, the following difficulty arises: If the blade moves with the stream, and at the same speed, no force can be exerted and the machine is consequently useless. If on the other hand the steam impinges on the blade we have loss due to shock as explained above. What third system of action is there?

Consider the case of a jet pressing upon a flat board, and suppose that the board is moving with one half the speed of the jet. The jet strikes the board and spreads out with shock and consequent evolution of heat. Further, the fluid that has acted on the board continues to move with the same speed as

the board itself, so that some energy (one quarter of that originally possessed by the jet) remains with the water, instead of passing to the machine—altogether a very poor contrivance. Now, instead of a flat board let us adopt the bucket shown in Fig. 15 (page 44). It will be seen that there is now no shock at the first approach, but, since the bucket is curved, the fluid presses upon its walls as it passes along, and leaves, as the curve of flow shows, practically without velocity. This bucket is therefore as efficient as any that can be produced.

Let the reader consider for a moment the nature of the action in the Pelton buckets, in its bearing on the questions of shock and of the communication of energy. The reader who appreciates adequately its merits, as stated in the last paragraph, possesses the same insight into the problems of hydraulic machinery as moved M. le Général Poncelet and his contemporaries to the creation of the turbine.

APPENDIX II.

ON FLUID MOTION.

THE laws enunciated in Appendix I apply to every form of matter, and therefore to the fluids whose action is chiefly interesting to the student of turbines. When we come to discuss the properties of fluids in greater detail, we find that we can no longer apply the same principles to every one, but must divide the objects of our inquiry into the classes of liquids and gases. The chief difference between the two is that a liquid is practically incompressible, whereas a gas is vastly compressible and perfectly elastic. Neither exerts any great amount of friction on bodies moving at ordinary speeds, and the friction of gases is peculiarly small.

All fluids are alike in this respect; that they exert the same pressure in every direction on a unit of surface placed at a given point in the fluid. This is termed the pressure of the fluid at that point. In the case of a liquid (which is heavy) the pressure depends on the depth below the surface, and is at every point sufficient to support the column of water above. At the depth H below the surface, the pressure is therefore MGH where M is the mass of unit volume of the water. Be it noticed that this is the same expression as that for the potential energy of unit volume of the water at the surface, and represents the work that it would do in falling to the depth H. We may take it that the pressure in a reservoir of gas (which is light) is the same throughout.

Suppose that there is a small hole at the depth H in a tank of water. The water will flow out; and we may suppose that it flows out at a speed V. Then, as it flows, the surface level falls, and by the principle of "conservation of energy," the

kinetic energy of the water flowing out must be equal to the potential energy lost by the water in the tank. The loss of potential energy is due to the fact that a layer of water of mass M has disappeared from the top of the tank. The same mass of water has made its appearance at the level of the orifice, flowing with velocity V. The loss of potential energy is therefore MGH, and the gain of kinetic energy is $\frac{1}{2}MV^2$. These being equal, we have $V=\sqrt{2GH}$, the velocity which the water would have acquired in falling from the level of the surface.

In the case of liquid under pressure there is no energy actually stored in the high pressure layer, by virtue of its pressure; the energy which gives force to a jet is really the possession of the top layer which is not under pressure. In the case of gas, on the other hand, the energy actually resides in the gas under pressure, any part of which would expand and do work even if the rest of the gas in the reservoir did not exist. But even in the case of liquids, since what actually happens when a hole is made in the tank is that a layer of liquid loses its pressure of MGH and acquires on the other hand a kinetic energy of $\frac{1}{2}MV^2(=MGH)$ per unit volume, it will be convenient to regard the pressure MGH as a form of specific energy residing in the liquid under pressure.

Now, if we consider the behaviour of liquid flowing in a pipe, it is clear that the sides of the pipe do no work (neglecting friction) on the liquid, and the total energy of the stream is therefore the same at any point (provided that we regard pressure, as in the last paragraph, as a form of potential energy). Now the velocity of the liquid varies, being inversely proportional to the section of the pipe at each point, and therefore the pressure must vary too, and we have **pressure + specific kinetic energy = constant.** If then the pipe be narrowed, the pressure falls for the increase of speed at that point, and the pressure rises again as the tube expands.[1]

[1] If we investigate closely the action which takes place in the pipe, we can see that, pressure not being a true form of energy, there is some force acting on an element of the fluid to change its

When a cistern is emptied through a pipe, the pressure of the water at the mouth of the pipe is the pressure of the atmosphere, and the speed of the water at the pipe mouth depends only on the drop in pressure between the two ends of the pipe. If the pipe is narrowed at the middle, so as to have a bell mouth, then the speed at the middle is greater than that at the end, and the pressure at the neck is less than atmospheric. The only limitation on the speed and pressure obtainable at the narrow neck by constructing a bell mouth is that the pressure cannot fall below zero. This is the secret of the bell-mouthed suction tube with which modern turbines are fitted; by means of this a perfect vacuum can be obtained at the point of discharge from the rotor.

The Vortex.

We have pointed out (App. I) that, when a body moves in a circle, some force must be acting on it, and it follows that, when a mass of water is spinning in a vortex, some force towards the centre must be acting on each particle of the

velocity. This force is, of course, the difference of the pressures exerted by the fluid before and behind.

Let the pipe section at a given point be S, the pressure P, the specific mass of the liquid M, and let the length of a certain element be X. Let the prefix d represent the change in a quantity between positions at the distance X apart.

Then the total pressure across a section of the pipe at any point is PS, which we shall call Q, and the mass of the element is MSX. It is a constant and we may call it K.

The force acting on the element is the difference between the total pressures on the two ends or $-dQ$, and the work done on the element as it moves through a distance X is $-XdQ$. The kinetic energy is $\frac{1}{2}KV^2$ and the change in the kinetic energy consequent on the motion is $\frac{1}{2}KdV^2$.

By the principle of conservation of energy, this change is equal to the work done, so that $\frac{1}{2}KdV^2 = -XdQ$, and therefore, integrating, $\frac{1}{2}KV^2 = -XQ +$ a constant.

Now $K = MSX$, and $Q = PS$, so that the last equation is equivalent to $\frac{1}{2}MSXV^2 + PSX =$ constant, or to $\frac{1}{2}MV^2 + P =$ constant, the fact which we set out to establish.

water. This force is in fact supplied by the pressure of the water in the outer rings of the vortex, and so it is clear that the further from the centre of the motion the greater the pressure must be.

Now there are two kinds of vortex: the free vortex, which it must be confessed is the more interesting, is the whirlpool formed by sucking rotating water towards the centre of the motion; it obeys the ordinary law of a stream that **pressure + kinetic energy is constant**, and consequently as the pressure drops towards the centre the speed of the water is vastly increased. The speed of the water is in fact inversely proportional to the radius of the circle in which it moves, and its angular velocity is, therefore, proportional to the inverse square of the radius. It follows that each ring rubs on the ring outside, and the friction so caused tends to check the motion. This is the vortex that would exist in the well of the antique turbine, described on page 13, if the rotor were not there. The insertion of the rotor prevents the increase of speed as the water approaches the bottom of the funnel, and transmutes the free vortex into a vortex of the second class.

This, the forced vortex, is that which would exist in a turbine wheel, if there were no flow of water through the wheel. The peculiarity of this vortex is that the water moves as a solid mass, every particle having the same angular velocity about the axis of the motion. The determination of the pressure prevailing at any point in this vortex involves a simple application of the integral calculus, which will be found in the foot-note.[1] The pressure may, however, be determined experimentally.

[1] Let the mass of unit volume of the liquid be M, the angular velocity, ω, and the pressure at a distance R from the axis, P.

Consider the equilibrium of a small rectangular block of liquid bounded by faces of area S perpendicular to the radius and distant R and R + dR from the axis. The mass of the element is MSdR and the force acting on it to preserve the circular motion is, therefore, $MSdR \times \omega^2R$. This force is supplied by the difference of the pressures on the opposite faces, these pressures being $S \times P$ and $S \times (P + dP)$. Therefore $SdP = MSdR \times \omega^2R$ or $dP = M\omega^2RdR$.

Integrating $P = \frac{1}{2}M\omega^2R^2 + \text{a constant} = \frac{1}{2}MV^2 + \text{a constant}$, where V

Suppose that a bowl of water—preferably one fitted with paddles fixed to the bottom, to ensure the proper rotation of the water—be spun on a turn-table. There is a forced vortex in the bowl, and it will be found that the free surface of the water adopts a parabolic form. If we imagine a horizontal plain through the bottom of the curved surface, then the height of any point in the surface above the plane is proportional to the square of its distance from the axis of rotation. Now the pressure at the point N (Fig. 82) is equal to the weight of the column of water AN, and is, therefore, proportional to the square of the length ON. The pressure at N is, therefore proportional to the square of the velocity at N, and measurement will show, as may be mathematically demonstrated, that this pressure is, in fact, that necessary to produce the velocity of the fluid at N.

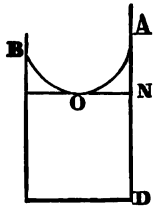


FIG. 82. DIAGRAM OF VORTEX SURFACE.

It is clear that the points O and N, though on the same horizontal plane are at very different depths below the surface. If the speed of rotation is fast, the paraboloidal surface is very deep and narrow, and AN may be very large in comparison with ON. For this reason we get the same effect as in Burdin's turbine with its huge rotating tank (Fig. 8) by the use of a very tiny high speed case wheel with closed channels. The substitution of speed for size is characteristic of modern engineering practice.

A curious and important fact results from this state of affairs: that water would be discharged from the bowl through an orifice situated at the point N, with a velocity relative to the bowl exactly equal to the velocity of the bowl at that point; so that if the orifice were fronted in a direction opposite to that of the bowl's motion, the discharged water would remain precisely at rest; and this is true of every point in the horizontal plane through the point O.

is the velocity at the point in question. The constant depends on the depth below O.

At any point in the plane of O the constant vanishes, since P and R both vanish at the point O.

It appears, then, that if water be discharged from a turbine wheel in a direction opposite to that of the wheel's motion, the absolute velocity of the water after discharge (and, therefore, the energy carried off by the water) is practically independent of the issue whether the discharge takes place from the outer or inner, upper or lower, surface of the wheel, or whether the flow is inward, outward, or axial; it depends only on the pressure and velocity at the point of admission.

APPENDIX III.

ON THE BEHAVIOUR OF GAS.

IN dealing with steam in a turbine or other engine cylinder we have to bear in mind that it is not a perfect gas, and does not obey completely the laws of gases; in particular, when saturated steam (that is, steam direct from the boiler) is expanded, a certain proportion of it condenses. We may say, roughly, that 4% of the steam condenses when the volume is doubled. Since, however, in all the best turbine practice superheated steam is used, we shall deal here only with such steam, and our work will be simplified by the fact that it behaves almost exactly as a perfect gas.

When gas acts without the communication of any heat from outside or to the outside, the operation is said to be adiabatic. The law of adiabatic expansion of gas is $P \times V^n =$ constant, P and V being the pressure and volume. In the case of superheated steam n is 17/16 so that the volume varies almost inversely as the pressure, but not quite to the same extent.

In discussing the pressure-velocity relations of steam and gas, we must consider two distinct cases. In the first place, where there is only small expansion, and a small drop in pressure, the gas behaves very much as does a liquid. If it expand from a pressure P to a pressure Q, then the drop in pressure is $P - Q$. Now the density of the gas behind is more or less proportional to P, and therefore the pressure $P - Q$ is that which would be due to a head of gas proportional to $(P - Q)/P$. The square of the velocity developed is, therefore, proportional to $(P - Q)/P$, and that is the ratio of expansion.

It follows that the velocity due to a small expansion of gas is approximately proportional to the square root of the ratio of expansion and does not vary much with the initial pressure.

In any case the velocity developed by a small expansion is very large in comparison with the ratio of expansion. Suppose that steam at 160 pounds pressure and 50° Fahr. superheat, expands to a pressure of 159 pounds through a nozzle. The volume of 1 pound of the gas is 3 cubic feet, and the head corresponding to a pressure of 1 pound per square inch is therefore 432 feet, so that the velocity developed is 170 feet per second, and the expansion is 0·57%. If, on the other hand, the steam be expanded to double its volume, the velocity developed is 1,500 feet per second, and if the expansion be two hundredfold, the velocity is only 4,000 feet. It is clear, then, that for a short time (during which the steam behaves very much as a liquid) the velocity increases out of all proportion to the volume, and (as with a liquid) the pressure drops where the pipe is narrowed and rises where the pipe expands again—in the Parsons turbine this is the type of action that takes place throughout—but when a certain limit of expansion (a little less than 100%) is passed, the volume begins to increase more rapidly than the velocity, so that the section of the pipe must increase as the pressure falls. Here we can no longer apply the principles of liquid motion, but must consider more intimately the nature of gaseous energy.

According to the modern theory, gas consists of a number of free molecules, each in motion; and the number of molecules to one pound of the fluid is invariable. When gas is heated the motion of these molecules is increased, and the mean kinetic energy of each molecule (and, therefore, the energy of 1 pound of the gas) is proportional to the absolute temperature, absolute zero being -461° Fahr.

Now if the volume of the gas be kept constant, the number of molecules per cubic foot is invariable; but all the molecules are moving, and, therefore, occasionally hitting the walls of the containing vessel, and the number which hit a

square foot of wall in one second is proportional to the velocity of the molecules. But the force of the blow dealt by each molecule is proportional to its momentum, *i.e.*, to its velocity; and the pressure on the wall of the vessel is, therefore, proportional to the square of the velocity of the molecules, that is to their kinetic energy, or to the absolute temperature of the gas (Boyle's law).

It is usual to say that gas contained in a vessel under pressure has potential energy, but as we have just seen it is probable that its energy is really kinetic; the accepted theory, at any rate, attributes the energy to the motion of the molecules. Now, if the molecular velocity be V, the energy of a mass M of the gas is $\frac{1}{2}MV^2$, proportional to the absolute temperature, and to the pressure of the gas. Let us endeavour to discover the ratio of pressure to energy.

Consider a cubic foot of gas contained in a cubical vessel and let the mass of the gas be M and the molecular velocity V. Then since all the molecules are moving in different directions, we may take it that M/3 are moving between each pair of opposite faces with velocity V.[1] Now the molecules

[1] The relation of pressure to molecular velocity can be worked out without the help of the somewhat crude assumption made in the text. We must premise that no momentum in any direction is destroyed by the impact of perfectly elastic molecules, so that we may neglect intermolecular impact without impairing the validity of our work.

Consider the impacts on an element, S, of surface during one second. The only molecules that can reach the surface within the second are those within a sphere of radius V. Now consider a ring within this sphere bounded by spherical surfaces at distances R and R + dR from the element of containing wall, and by cones making angles A and A + dA with the normal to the element S.

The volume of this ring is $2\pi R^2 \sin A.dA.dR$. The distance of every point in the ring from the element S is R, and the obliquity of the element to the path of a molecule coming from any point in the ring is 90° − A. The solid angle subtended by the element at any such point is, therefore, $\frac{S\cos A.}{R^2}$

Now the molecules within the ring are moving in every direction, and the proportion of them striking the element S is $S\cos A/4\pi R^2$. The whole mass of molecules from this ring striking the element is

are perfectly elastic and move to and fro with no loss of speed. Every time that a molecule travels through a distance of 2 feet, it hits the same face once. Each of the M/3 molecules, therefore, hits a given face V/2 times in a second, and at each blow its velocity is reversed, so that the force of the impact is 2V times the mass of the molecule. The whole pressure on the face due to this molecule is, therefore, V/2 times 2MV, or V^2 times its mass. Thus the total pressure on the face is $M/3 \times V^2$. The energy of a cubic foot of gas is $\frac{1}{2}MV^2$, and, therefore, the pressure on a square foot of the containing vessel (expressed in poundals) is equal to 2/3 of the energy of a cubic foot of gas.

The energy of a pound of gas must, therefore, be $3/2 \times 144 \times 32{\cdot}2 \times$ (pressure per square inch) $\times$ (cubic feet to the pound).

Having given the pressure of a gas and its density, we are now in a position to say what is the molecular velocity of the gas; and that is, of course, the mean velocity which the gas will develop on complete expansion.

If, then, gas enclosed in a receiver were discharged from a properly shaped nozzle, the mean square of its velocity of discharge would be the molecular velocity; but it is quite clear that, since the pressure in the receiver falls continually as the gas is discharged, that part which escapes first escapes fastest, and its velocity will be considerably more than the molecular velocity of the gas. Now in dealing with boiler steam we have a continual supply of fresh vapour forming in the boiler, so that the case is practically that of the first discharge of gas

M.sinA.dA.dR.ScosA/2. The change of velocity of each molecule at impact is 2VcosA, since it strikes the surface obliquely, and the pressure on the element due to this ring is, therefore,

$$MVS\sin A\cos^2 A\,dA\,dR.$$

To find the whole pressure on the element, we must integrate this expression throughout the hemisphere.

The resulting expression is

$$MVS\int_0^{\frac{\Pi}{2}}\int_0^{V}\sin A\cos^2 A\,dR\,dA, \text{ or } MV^2S\int_0^1\cos^2 A\,d\cos A$$

which reduces to $MV^2S/3$; so that the pressure on an area S is $MV^2S/3$, and the pressure on unit area is $MV^2/3$ as found above.

from the receiver. It is required to find the relation of the velocity of discharge to the molecular velocity and pressure.

In the receiver before mentioned (which we will suppose to be very large), a cubic foot of gas, in the course of discharge, turns its own molecular energy into kinetic energy; but besides the work done by the molecular energy of the gas escaping, which is $\frac{1}{2}MV^2$, there is work done by the gas pressing behind. The pressure per square foot is $\frac{1}{3}MV^2$. Now, if there were a piston 1 foot square between the gas discharged and the gas behind, that piston would have to advance 1 foot in order to clear out a cubic foot of gas, and the work done by the gas behind would then be $\frac{1}{3}MV^2$. The whole kinetic energy of the discharged gas is, therefore, $\frac{1}{2}MV^2 + \frac{1}{3}MV^2$, or $\frac{5}{6}MV^2$ altogether. If, then, it were discharged into a perfect vacuum, the velocity of the stream would be $V \times \sqrt{\frac{5}{3}}$.

This velocity will not be attained by steam escaping through a simple orifice, because the various molecules which use the opportunity of escape, rush out in all manner of different directions. The mean velocity of the stream is therefore only that due to the pressure behind, or $V \times \sqrt{\frac{2}{3}}$, and the jet bushes out so soon as it is clear of the orifice.

To attain the full velocity of flow, it is necessary to catch the wandering molecules and to direct them in the way they should go. This is done by means of a divergent cone attached the nozzle, which reflects each particle of gas more and more into the line of flow at each impact, so that the pressure falls and the velocity rises while the gas flows down a pipe of increasing section. We have seen that the effect of such a pipe on water would be precisely opposite.

The flow of steam when not strongly superheated, and even when superheated, if the ratio of expansion is very large, is further complicated by the condensation of a portion of the vapour. The effect of this is to reheat the steam not condensed, by the latent heat given off by the water in condensing. The reheated steam then escapes with a greater velocity than that

arrived at by our calculation, while the water drops travel more slowly. The consequences of this action are discussed on pages 229-231 in connection with the economy of the steam turbine.

APPENDIX IV.

ON THE GYROSCOPIC EFFECT OF TURBINES.

BOTH the advocates and opponents of the turbine as an engine of marine propulsion have recognized that it introduces a new factor of some importance, whether small or great, into the stresses of the vessel in a seaway, and it has been maintained on the one hand that the gyroscopic effect of the high speed rotor will increase the steadiness of the vessel in a head sea, and, on the other, that it will add seriously to the straining of the hull.

The large low speed turbines used for mercantile marine work at the present day can have no serious effect in either direction, owing to the very slow pitching of the hulls of large vessels; but it may be worth while to devote a little more serious thought to the state of affairs prevailing in those smaller vessels where high speeds of running are adopted, as in the earliest turbine vessels and in the torpedo boat destroyers now under construction.

The phenomena of gyroscopic action are well known. If a heavy body be rotating, and an effort be made to turn the axis of rotation into a different position, the effect of the couple applied is to turn the axis indeed, but at right angles to the direction intended, and the effort required is out of all proportion to the effect accomplished. This is familiarly instanced by the top, the axis of which, thanks to the effort of gravity to lay it down horizontally, turns itself in a horizontal circle instead.

So a high speed steam turbine resists the effort of seas, lifting the bow or stern of the ship, to sway the turbine in a

vertical plane, and endeavours to sway itself in a horizontal plane, thereby introducing stresses in the hull of the vessel. The magnitude of these stresses is what we have to examine, and, in order to do so, we must first arrive at some idea of the nature and cause of the action.

We have pointed out (App. I) that every rotating body has an angular momentum about its axis proportional to ω the angular velocity, and to I the moment of inertia of the body about its axis. Now angular momenta, like velocities, can be compounded according to the triangular law, and therefore if a turbine be rotating about a horizontal axis AB, with an angular momentum represented in magnitude by AB, and if it be required, in order to accommodate the pitching of the ship, to change its axis of rotation to the position AC, this can only be done by adding to the original angular momentum an angular momentum about the line BC, represented in magnitude by that line. If the angle BAC be ϕ, a small angle, then the length of BC will be $AB \times \phi$. The angular momentum represented by AB is $I\omega$, so that represented by BC must be $I\omega\phi$. If, then, the axis turn through an angle ϕ in the time t, the rate of communication of the angular momentum round BC the vertical axis, will be $I\omega\phi/t$ or $I\omega \times$ (rate of turning of the axis AB), and this is the horizontal couple that must be applied to the turbine to secure the vertical turning of its axis.

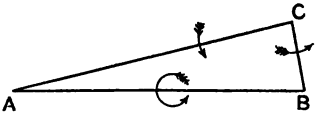


FIG. 83. DIAGRAM OF ANGULAR MOMENTUM.

Turning now to the application of these principles to a torpedo destroyer, we shall make the following assumptions, all more or less close to the mark:

(1) That the mass of the rotor is three tons.

(2) That the radius of gyration of the rotor is 18 inches. (I is then approximately 27/4 foot-ton units.)

(3) That the maximum pitch of the vessel is 5° from the horizontal.

(4) That the complete oscillation up and down is performed in 6 seconds.

The direction of the turbine shaft is changing most rapidly when it is horizontal, and the rate of change is then 4/27 of a radian per second. The couple $I\omega \times$ (rate of turning of the shaft) becomes then $27/4 \times 4/27 \times \omega$, and the full speed will be about 720 revolutions, which gives $\omega = 75{\cdot}5$. The horizontal couple that must be applied to the turbine is therefore 75·5 foot-second-ton units, or, dividing by g, 2·34 foot tons. If the bearings of the turbine are 10 feet apart, this amounts to a load on each bearing of 0·234 ton, or one-sixth of the weight normally carried by the bearing.

It is clear that the strains set up are not, in any case, very serious. If the bed-plate is properly put in, so as to distribute the load over the hull, no serious strains will be caused even by three turbines all running the same way. If the turbines run in opposite senses, then their tendency, when the bow of the ship lifts, is to turn in opposite directions, and so to tear the bed-plate asunder. Where a set of two or four turbines are fitted, the whole strain will be borne by the bed-plate, and none will be communicated to the hull when the whole set are running (contra when the starboard engines are going ahead, and the port engines astern).

It seems proper to point out that the rotors of the *Cobra's* turbines were much lighter than those here considered and were of smaller diameter. Now the moment of inertia is proportional both to the mass of the rotor and to the square of its radius of gyration—roughly then to the fourth power of its diameter multiplied by its length. This is one of the principal reasons why the Parsons turbine, which is distinguished from all other makes by its smaller diameter (and greater length) has hitherto been found by far the most suitable for sea-going ships; and this renders it inconceivable that the turbines of the *Cobra* should have been responsible for her lamentable fate.

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